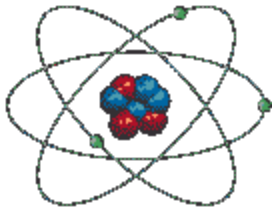
MINISTERIO
DE CIENCIA E
INNOVACIÓN



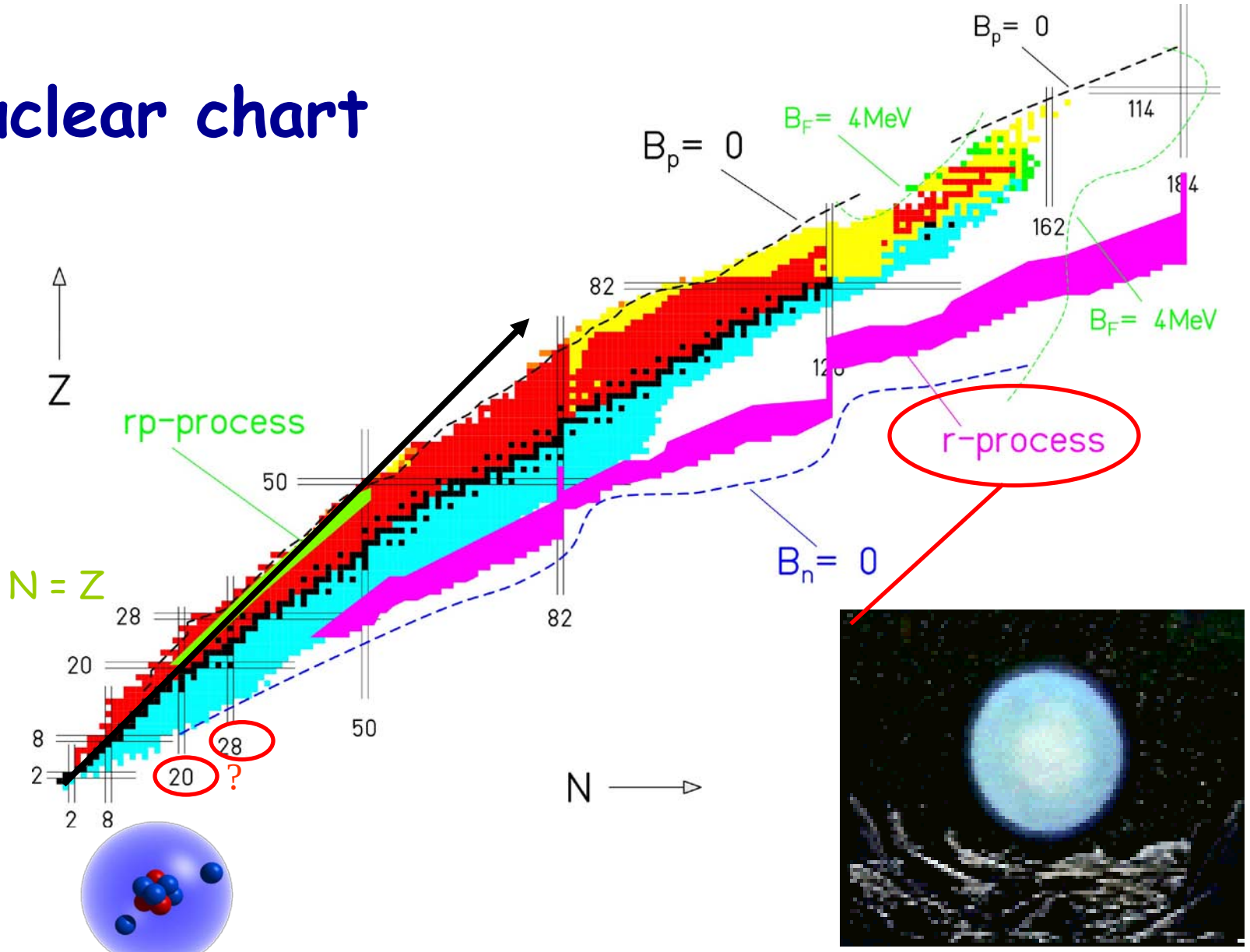
Olof Tengblad
Instituto de Estructura de la Materia - CSIC

Experimental Nuclear Physics

How to produce & study exotic nuclei

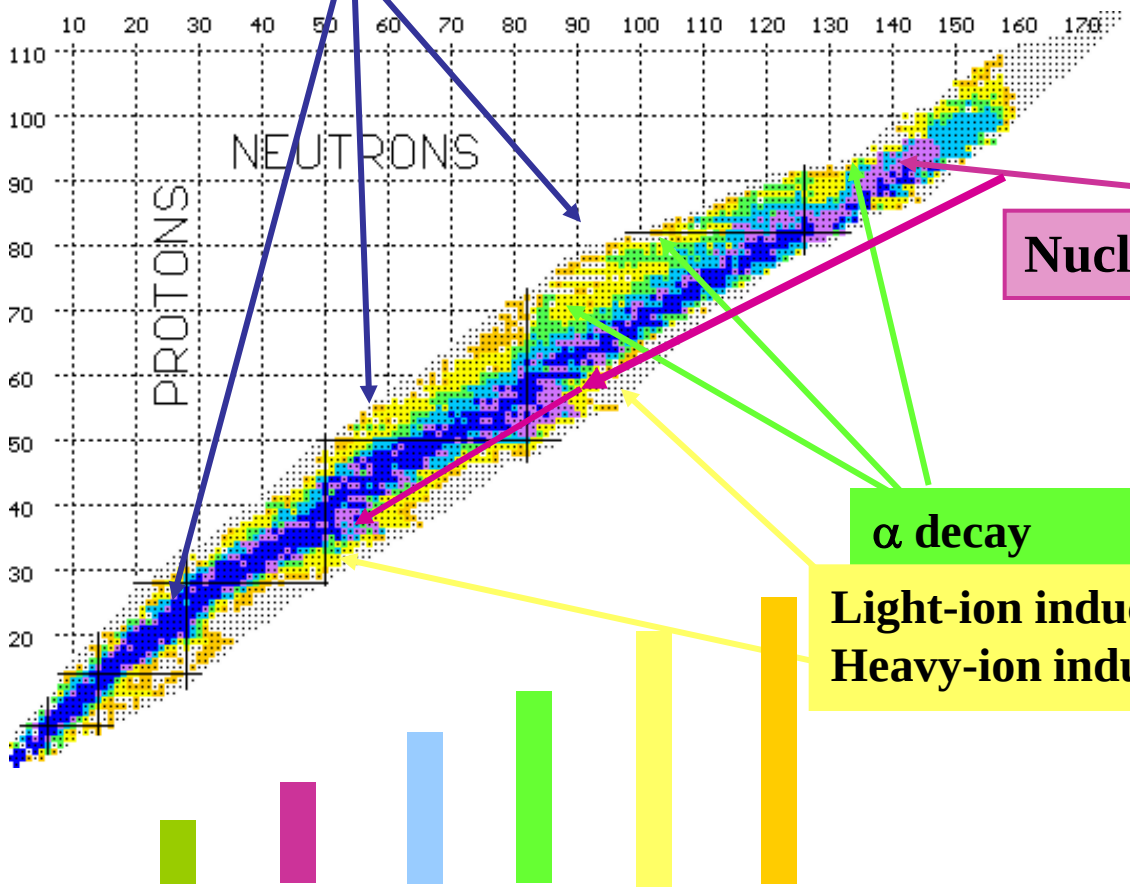
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Nuclear chart



Knowledge hand in h

Projectile and target fragmentation
+
In-flight separation



Nuclear Reactors: n + U

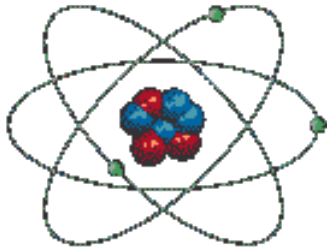
α decay

Light-ion induced spallation
Heavy-ion induced fusion

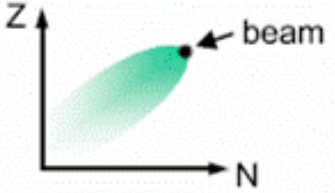
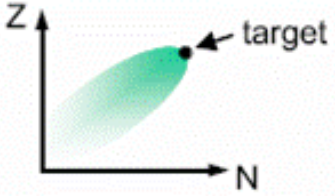
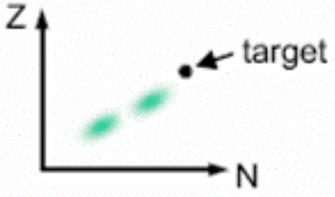
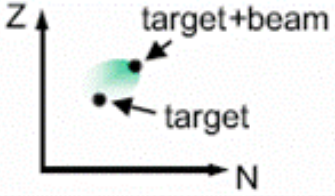
<1940	1940	1950	1960	1970	1980
495	822	1244	1515	2010	2270

outline

- Knowledge hand in hand with production
- Why we need several facilities
  - 11Li an interesting example
- Production methods
  - In flight
  - ISOL
- ISOLDE
- ^{12}C studied at 5MV tandem

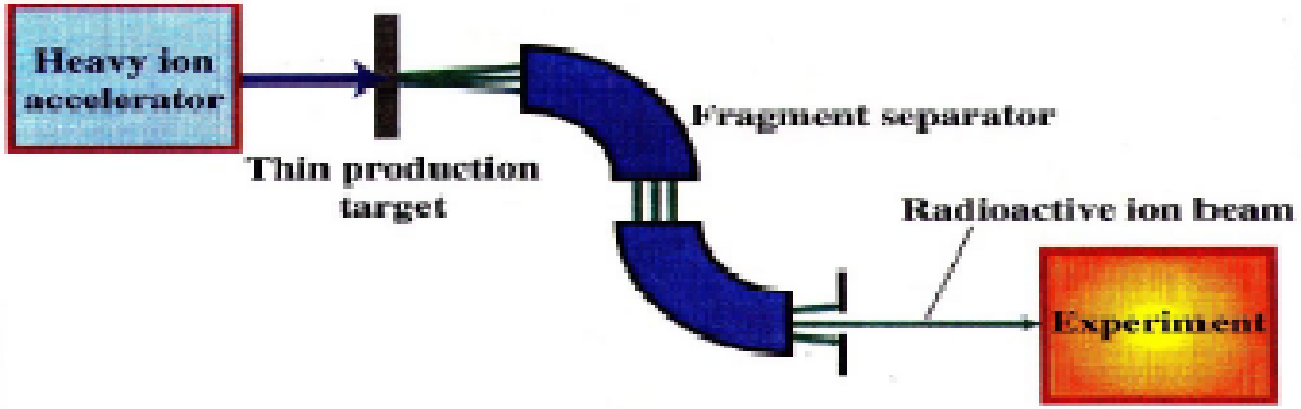


Production methods

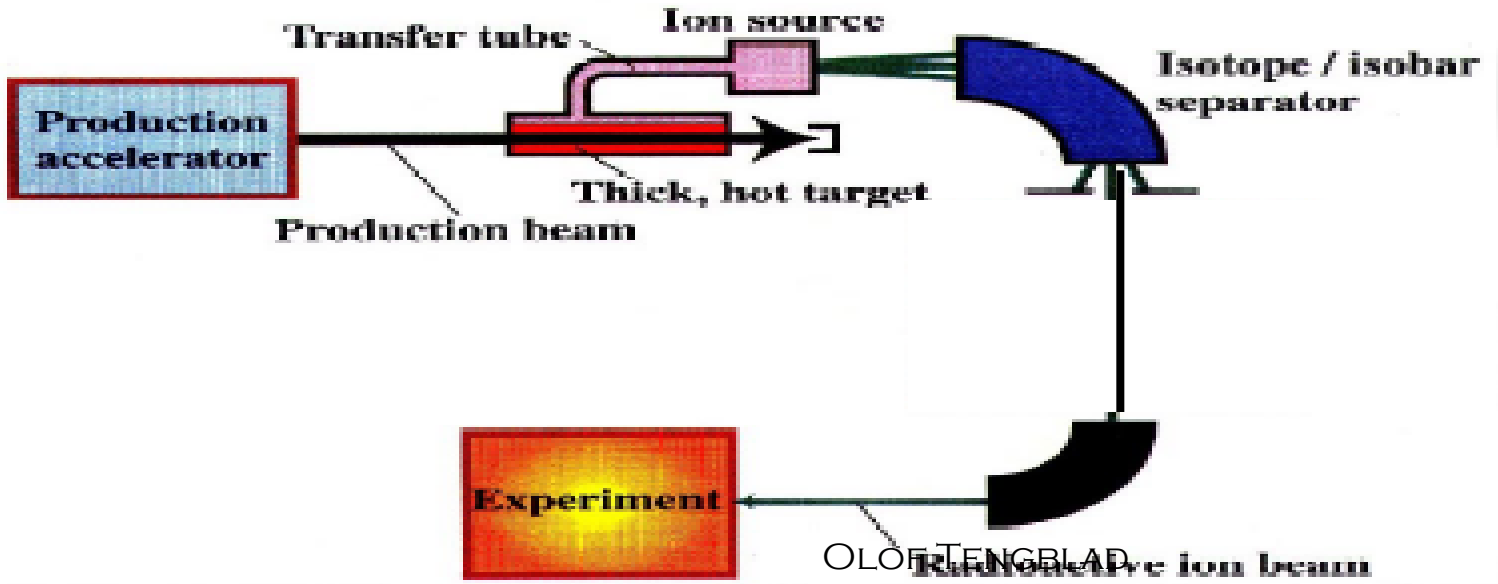
Beam → target → products		high energy (>> thermal energy)	many products	
heavy ion +	fragmentation	$v_{product} = v_{beam}$	up to 1000	
p +	spallation	few MeV/u	up to 1000	
p/n +	fission	~1 MeV/u	few 100	
heavy ion +	fusion-evaporation	$E_R = \frac{m_p}{m_p + m_t} E_P$	few (≤ 20)	

Radioactive Beam Production

Projectile Fragmentation

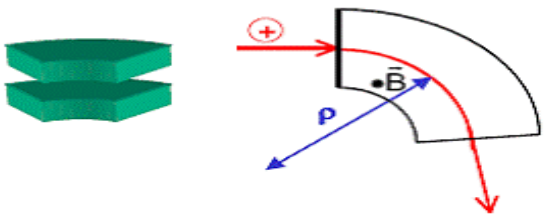


ISOL



Separation at high energy

magnetic dipole



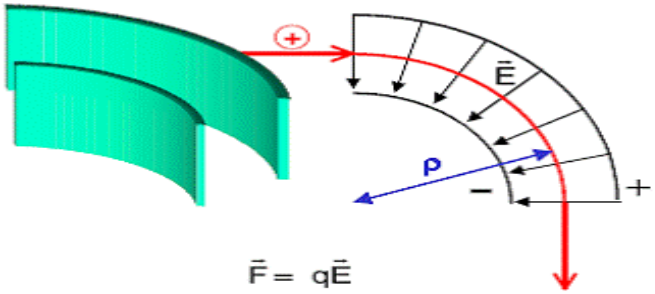
$\vec{F} = q\vec{v}\times\vec{B}$

$B\rho = \frac{mv}{q} \quad [T\cdot m]$

magnetic rigidity

dispersion

electric dipole



$\vec{F} = q\vec{E}$

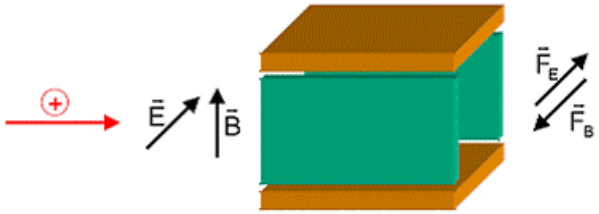
$E\rho = \frac{mv^2}{q} \quad \left[\frac{J}{C}\right]$

electric rigidity

Separation at high energy

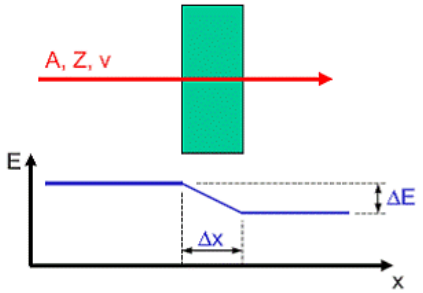
velocity filter

Wien filter, E-cross-B filter



charged partides with velocity $v = \frac{E}{B}$ are not deflected

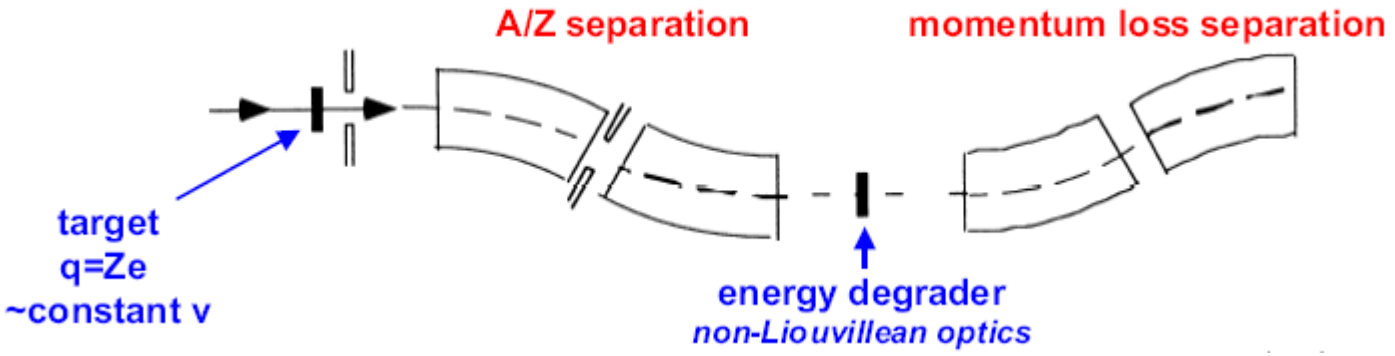
Energy degrader



stopping power $S \equiv -\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{A\,Z^2}{E}$

→ straggling (spread) in energy and angle

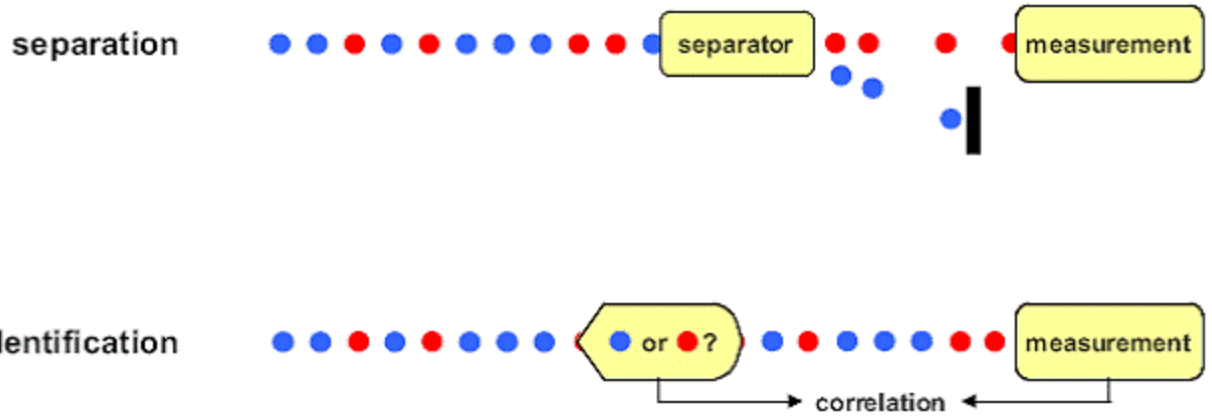
Fragment Separator - FRS



magnetic rigidity $B\rho = \frac{m\,v}{q}$

$$(B\rho)_1 \propto \frac{Z+N}{Z} \qquad v_2^2 = v_1^2 - d\,\frac{Z^2}{Z+N} \qquad v_2 = v_1 \frac{(B\rho)_2}{(B\rho)_1}$$

Separation & identification methods



	high energy *beam*	thermal energy *cloud*
separation	• magnetic dipole • electric dipole • velocity filter • energy degrader	• ionization • ion trap
identification	• time-of-flight (TOF) • total energy • energy loss (ΔE) • magnetic rigidity	• stopping range • radioactive decay

in-flight

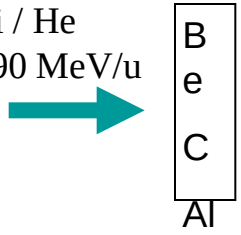
stop & go (ISOL)

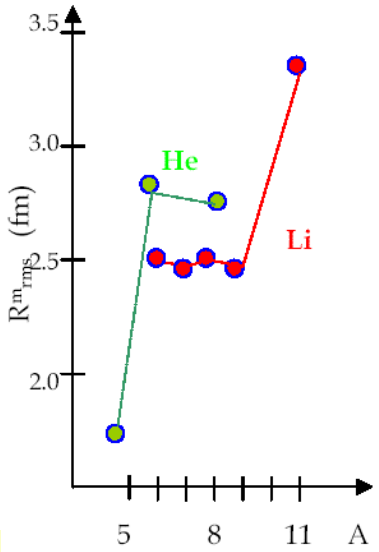
An example: ^{11}Li and the neutron halo

Inicial experiment

Tanihata et.al.
Phys.Rev.Lett 55(1985)2676

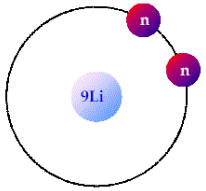
Li / He
790 MeV/u



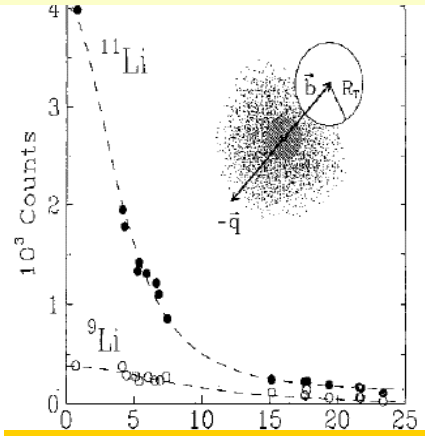


Model

P.G. Hansen, B. Jonson
Europhys. Lett 4(1987)409



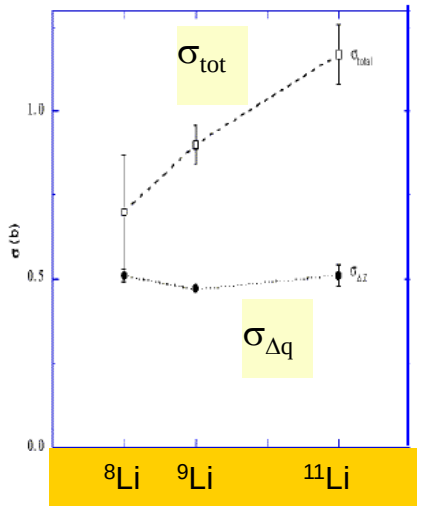
R. Anne et.al.
Phys.Lett B250(1990)19



Neutron Angular distribution

Model verification

B. Blank et.al.
Z. Physik A343(1992)375

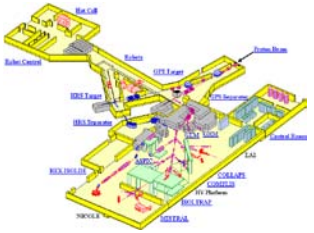


To get the full picture we need to study at different energies

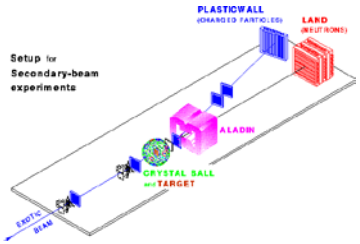
Elastic Scattering

Reaction Cross Sections

Spins Moments



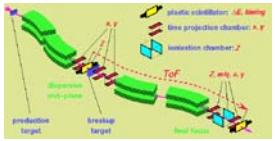
Masses

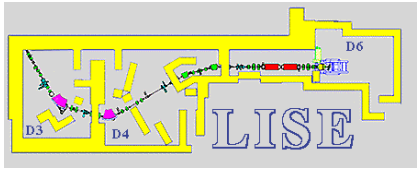


Beta Decay

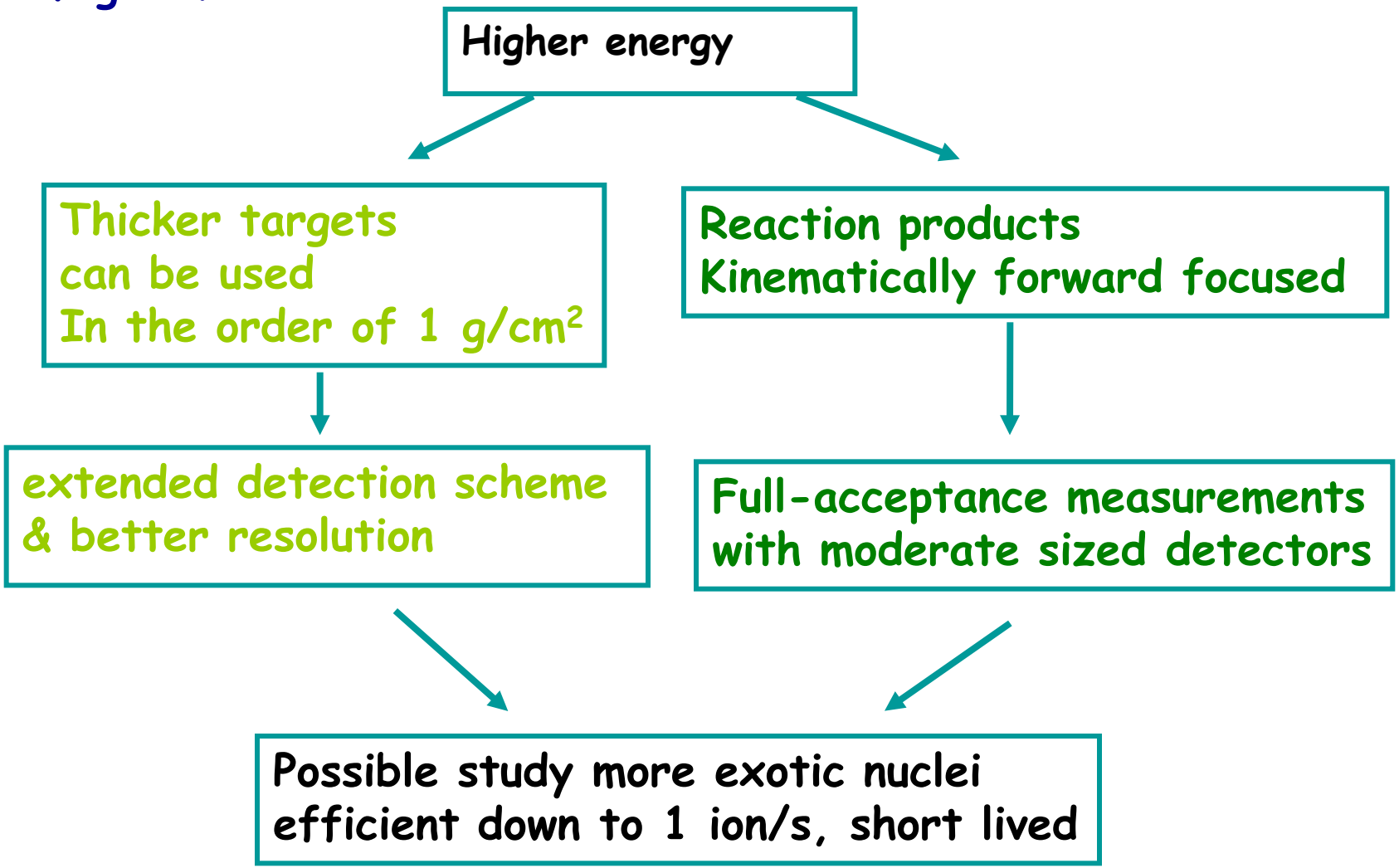
Momentum Distributions

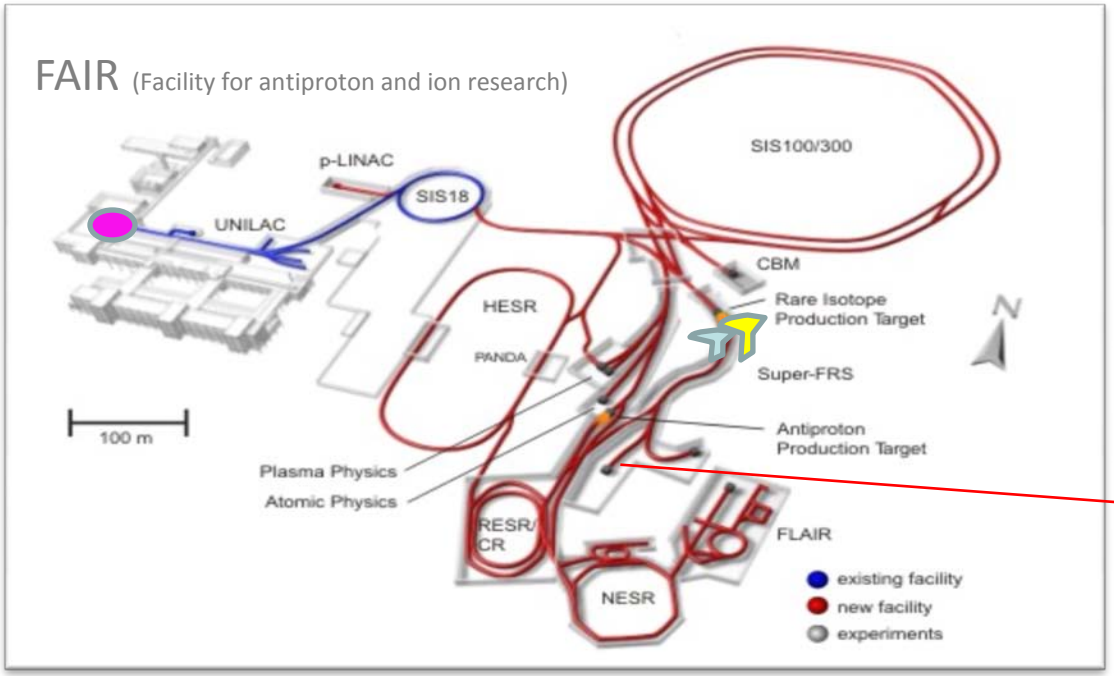
Unbound Nuclei





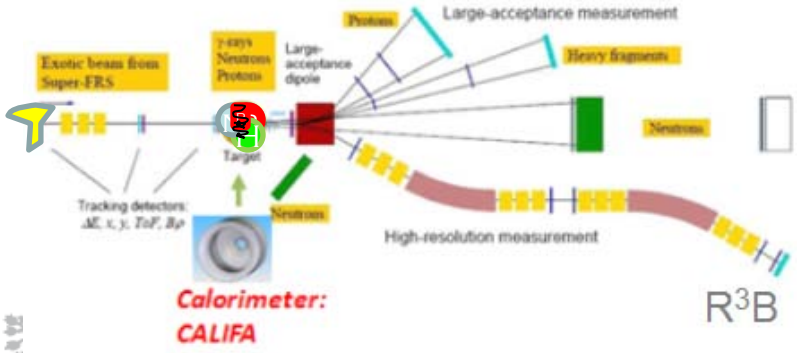
In flight method





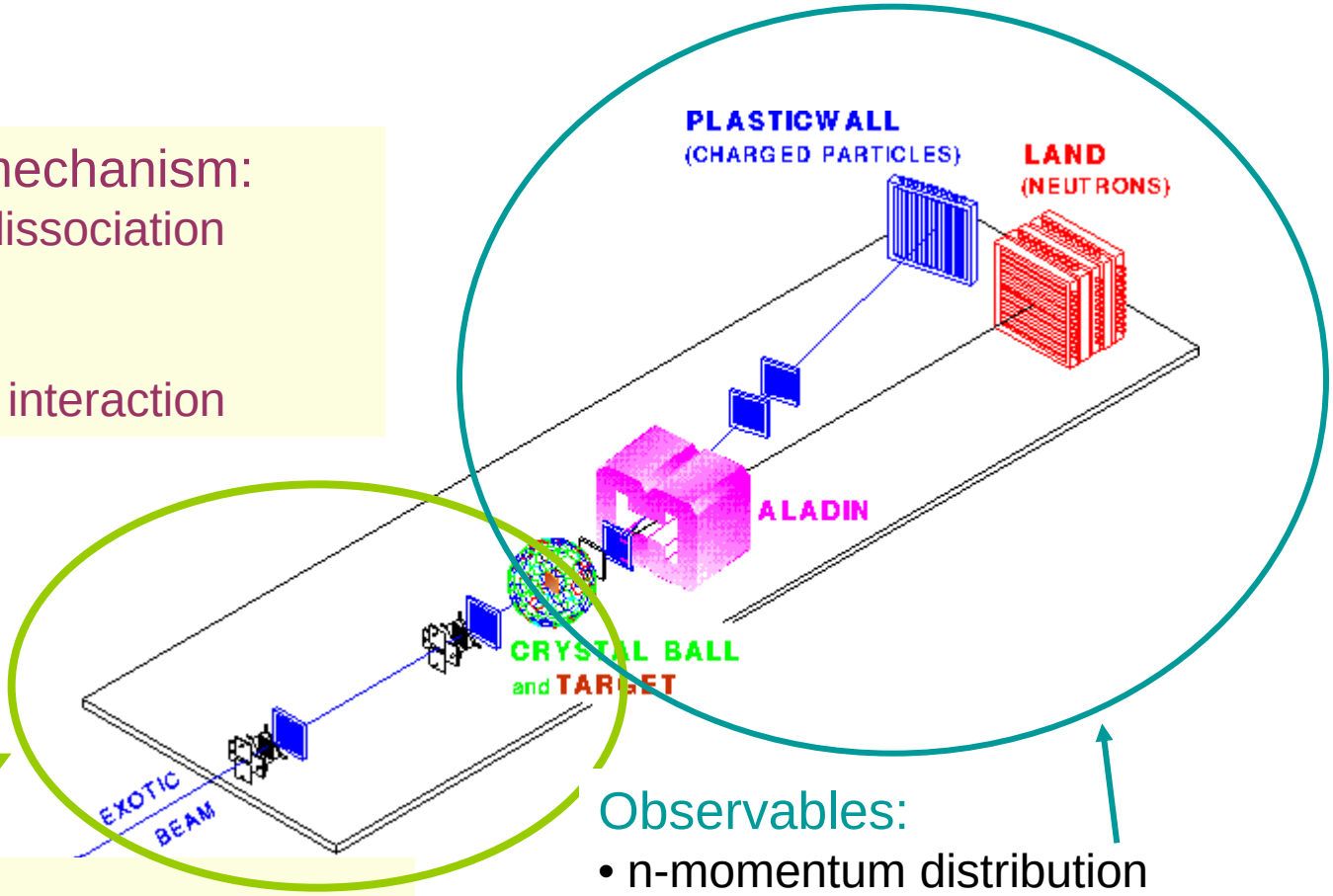
R^3B

FAIR: Facility for Antiproton and Ion Research



High Energy Reaction Studies: Present Cave C @GSI

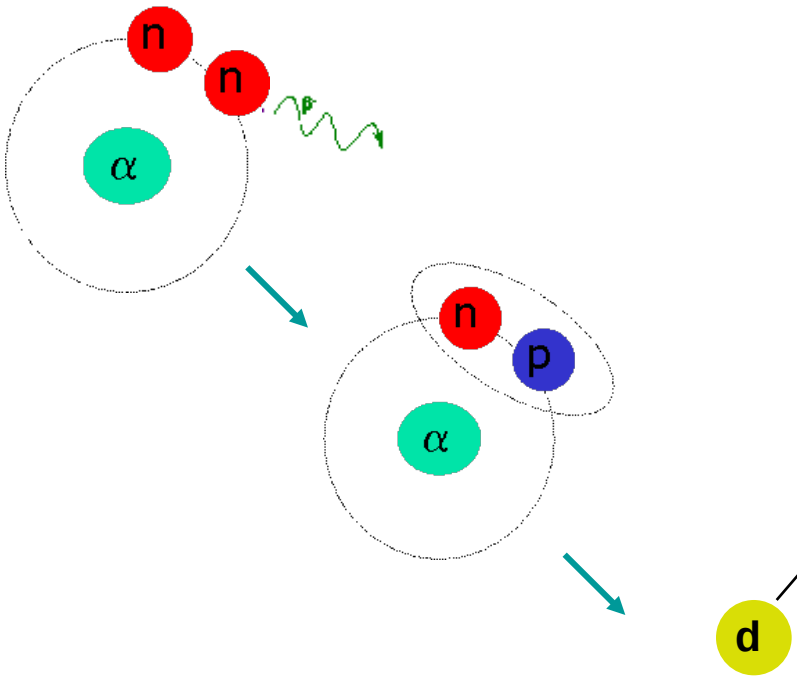
Reaction mechanism:
- Coulomb dissociation
- Diffraction
- Absorption
- Final state interaction

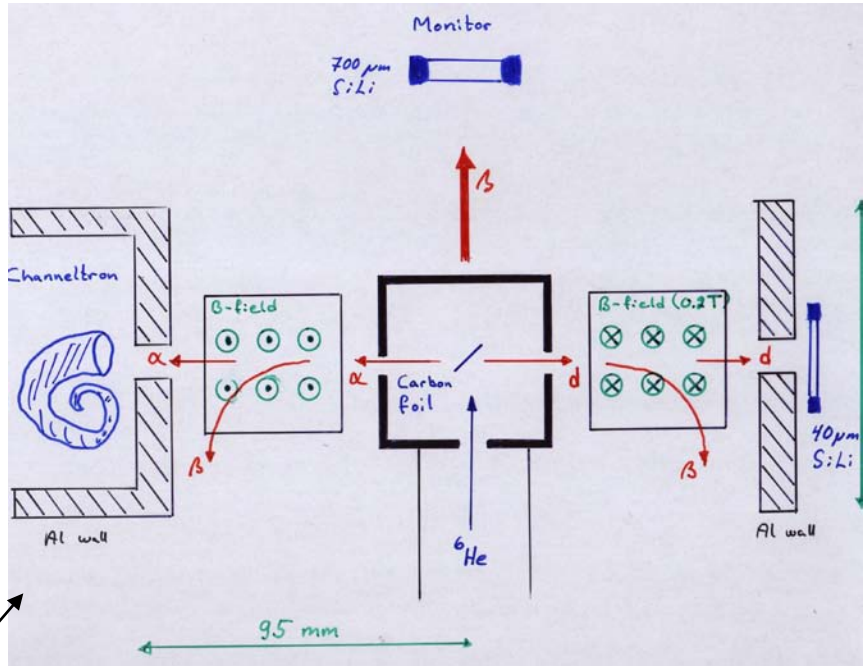


Exp. variables:
- Beam energy 30 → 600 MeV/A
- Target material C → Pb
- Projectile ^{6}He → ^{19}C

Observables:
- n-momentum distribution
- Charge fragment momentum
- Invariant mass
- Angular correlations

We can study this sytems also in beta decay but then we need the ISOL method





6He: **α-core with a 2n halo**

First observation of beta-delayed deuteron emission
Phys Let B235 (1990) 30

24h: **147 coincidencias → branching 2.8 10^{-6}**

Beta decay studies: We need pure beams!

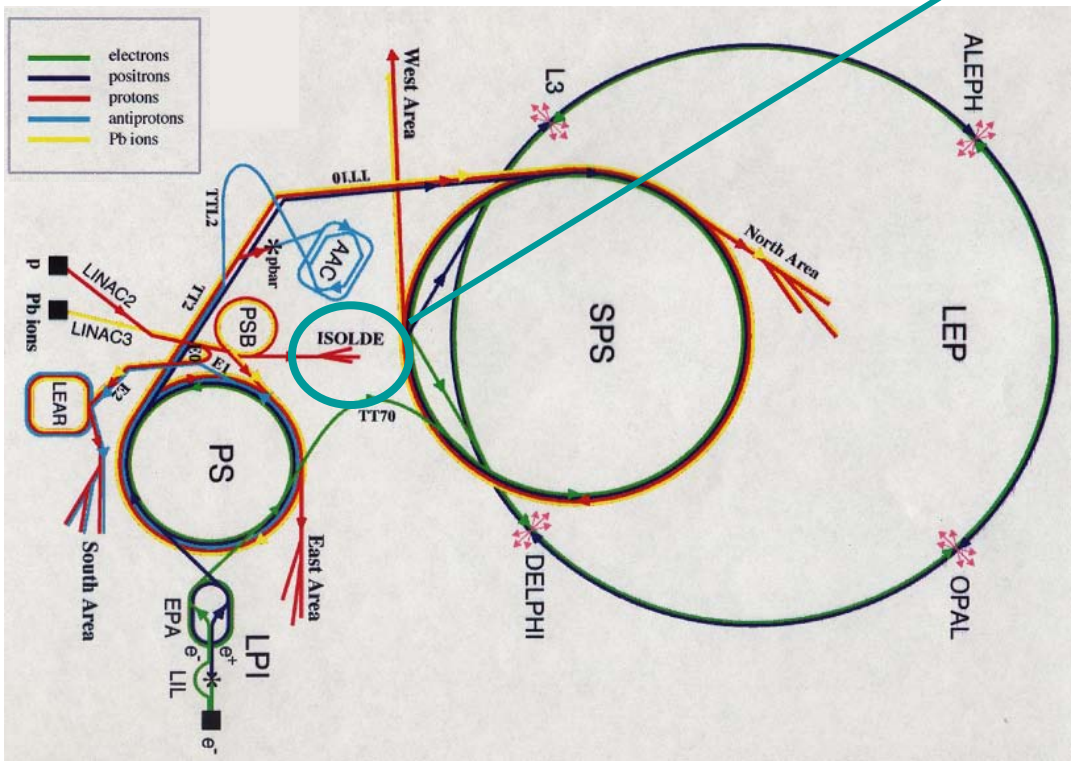
- **free from isobaric contamination**
- **The incrediences are:**

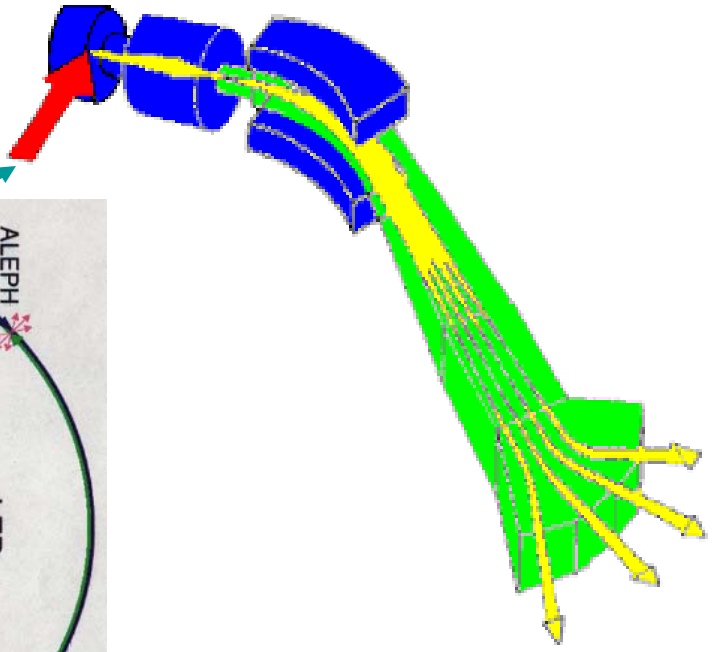
- **Primary beam**

- **Target and ion source**
  - **Chemistry**

- **Magnetic separation**

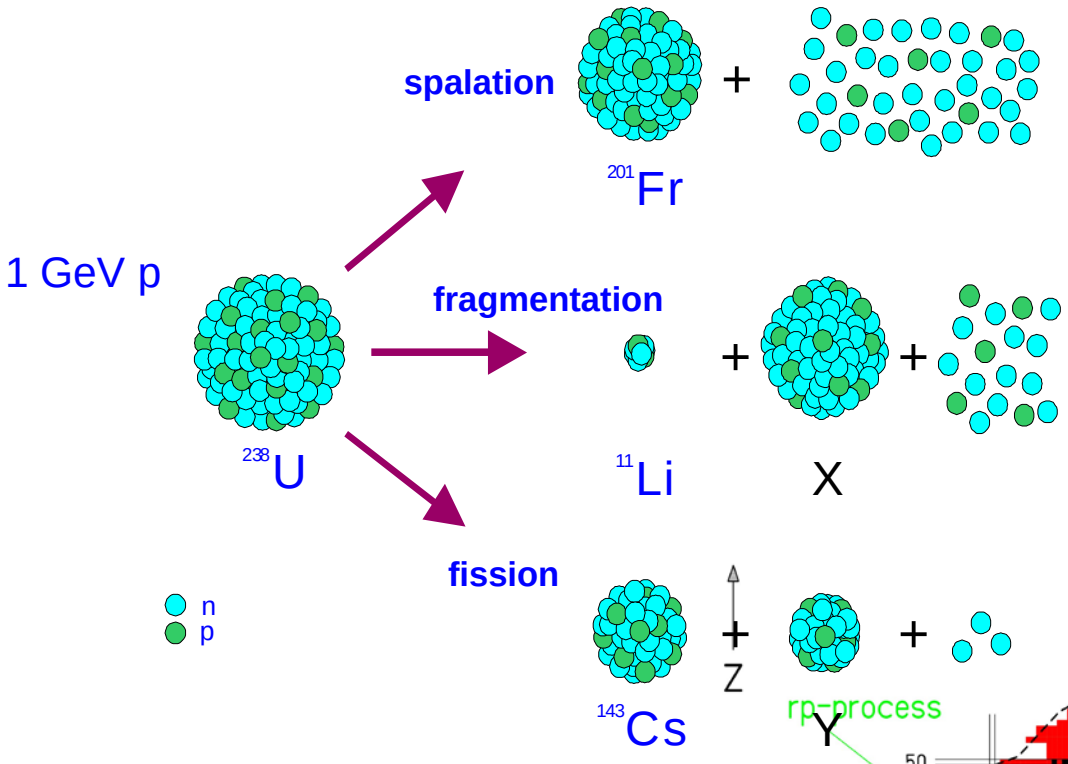
Primary Beam: CERN PS Booster → ISOLDE





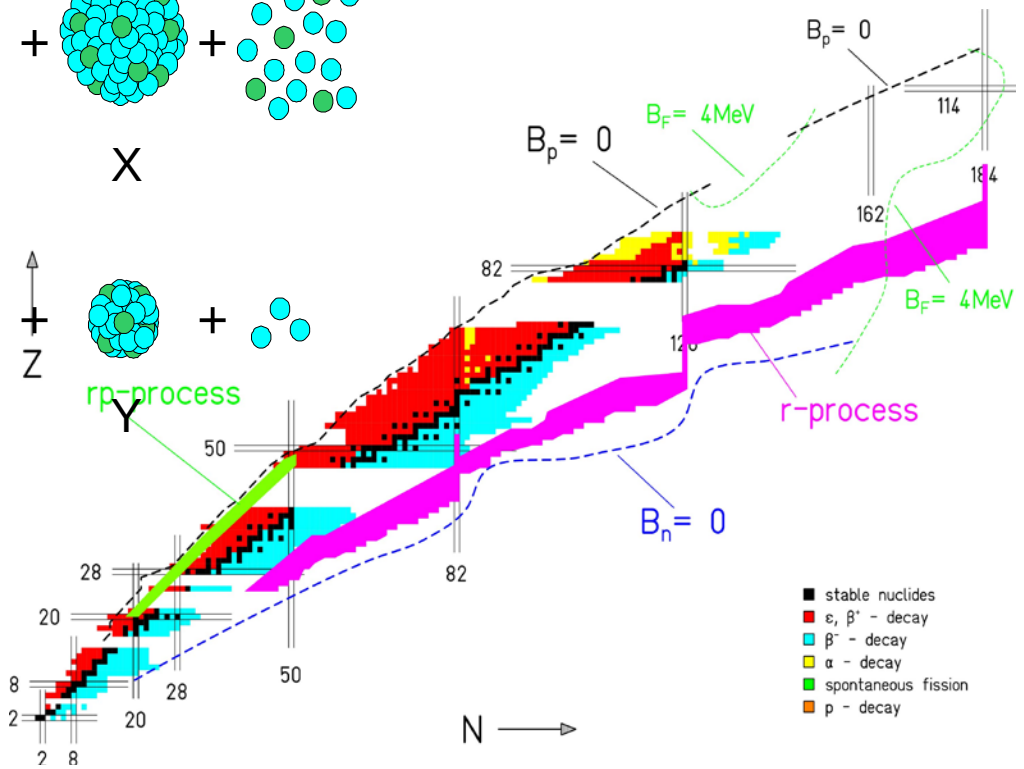
Beam: Protons 1.4 GeV
Intensity: 3 10^{13} p/p
pulse: 3μs
Repetition: 0.5-1Hz

Isotope production

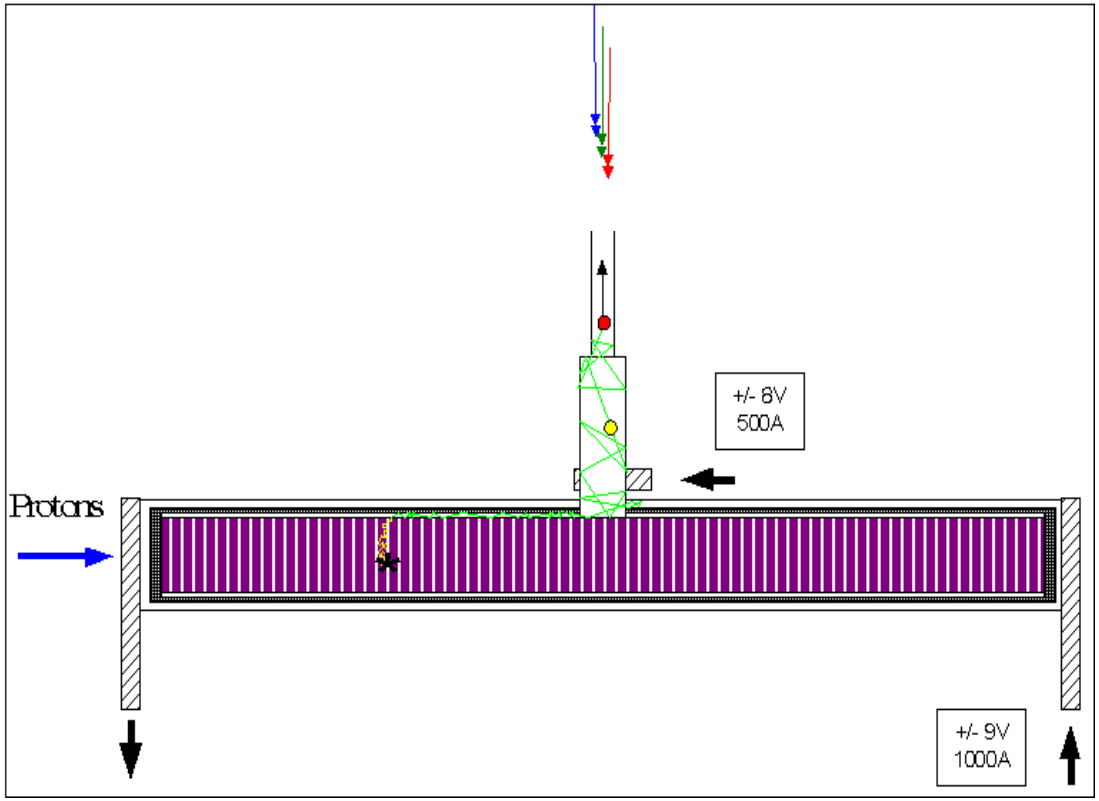


Exotic ion production

Nuclei chart @ ISOLDE

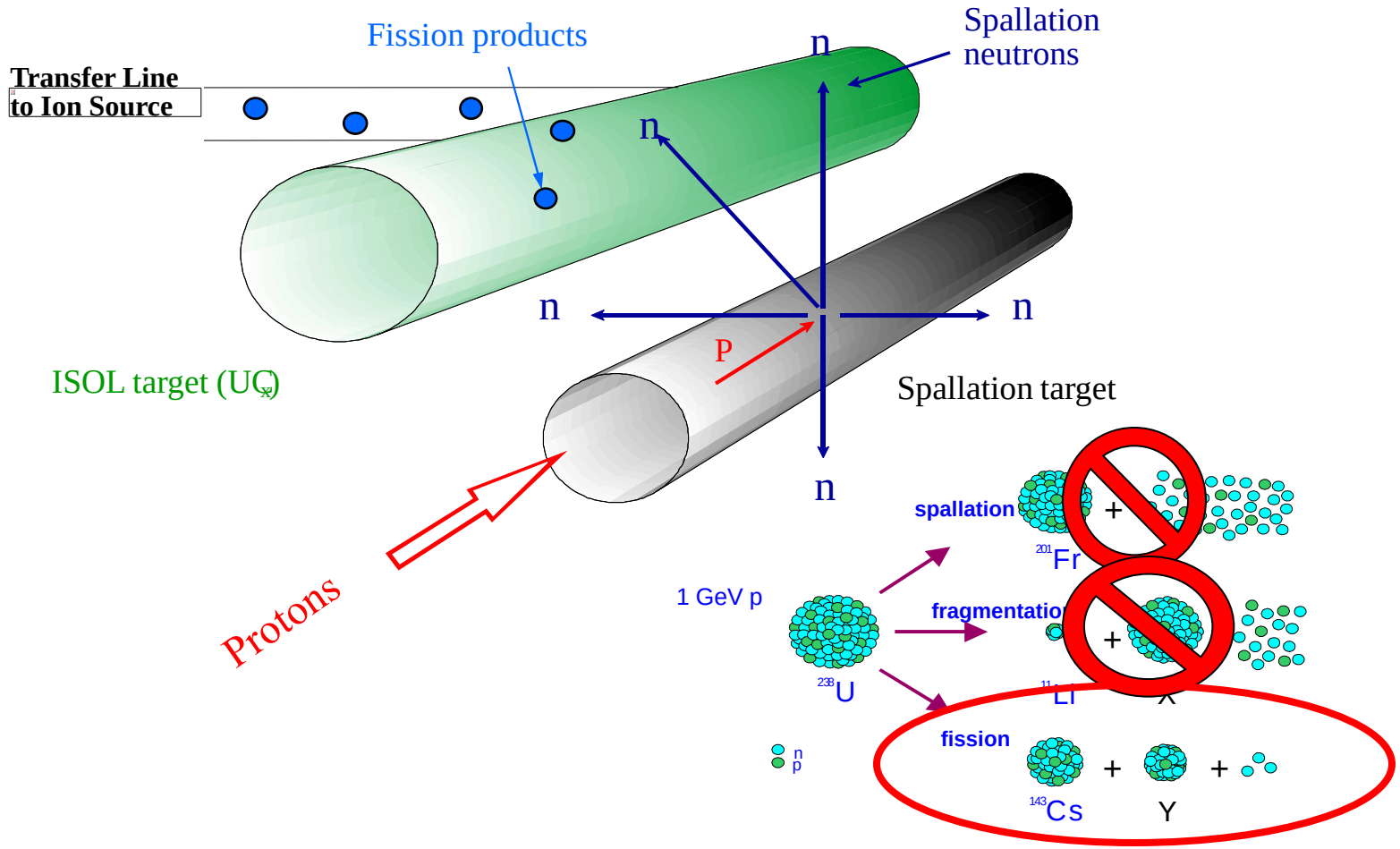


Target – Ion-source matrix: a chemical laboratory

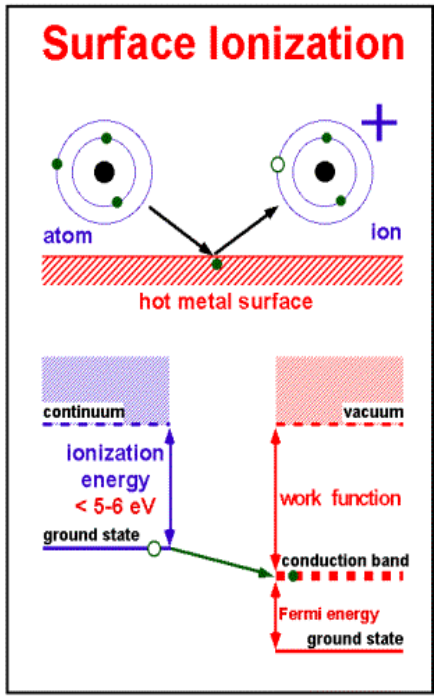


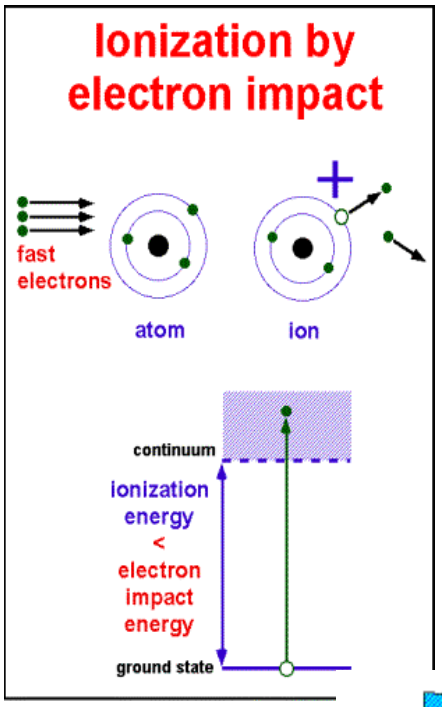
- Container: 20 x 2 cm cylinder of Ta
- Material:
  - Liquid La, Pb, Sn
  - Metal foil/powder Nb, Ti,
  - Oxides CaO, MgO
  - Carbides SiC, UC, ThC
- Ion-source
  - Surface
  - Plasma
  - Laser
- Fluorination CF4 or SF6

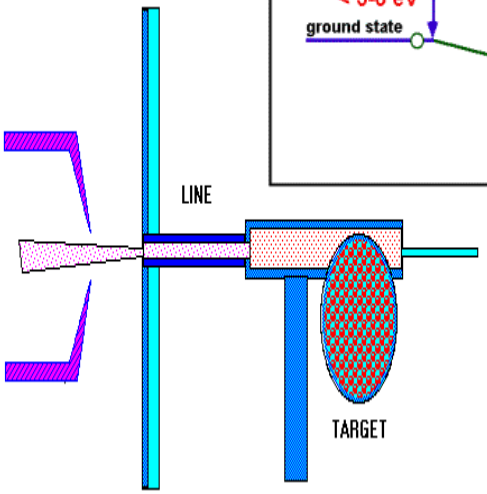
Converter target

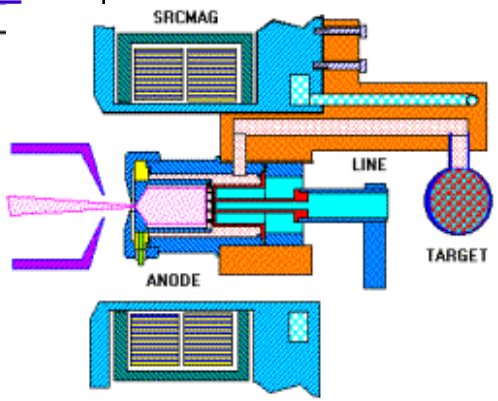


Surface & plasma ionization

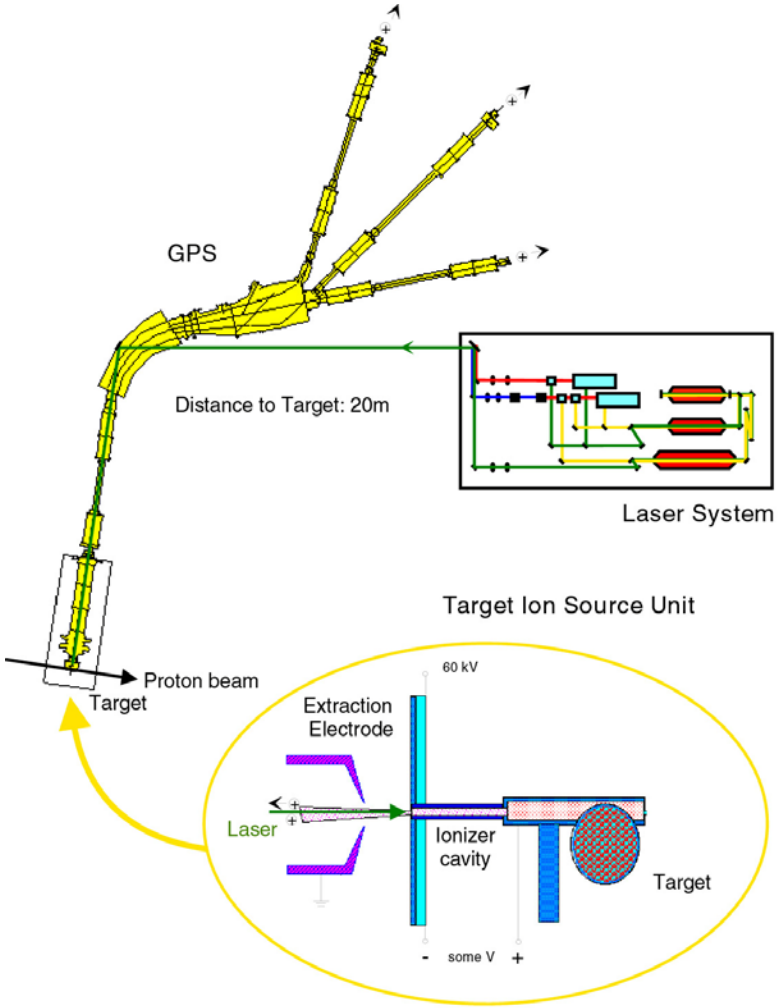


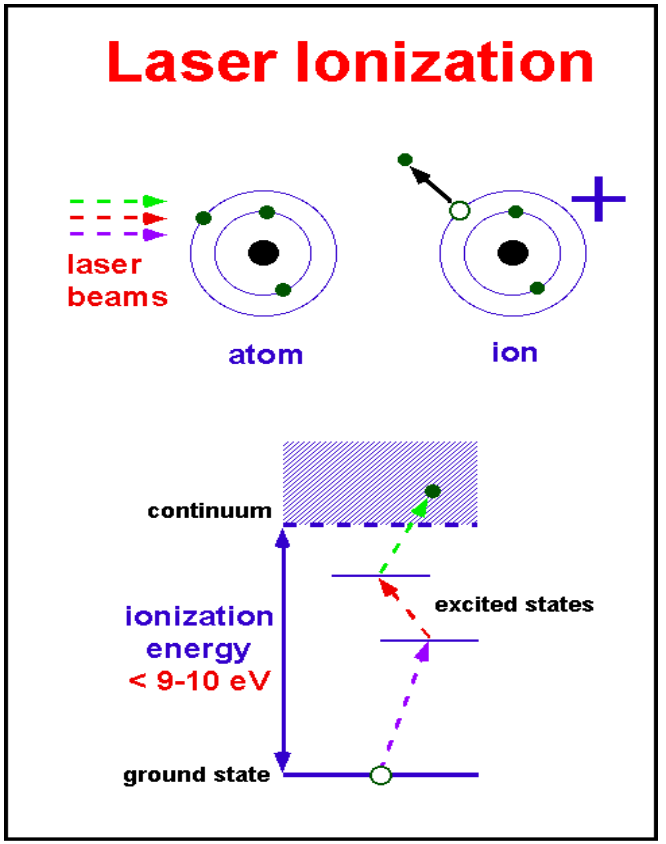






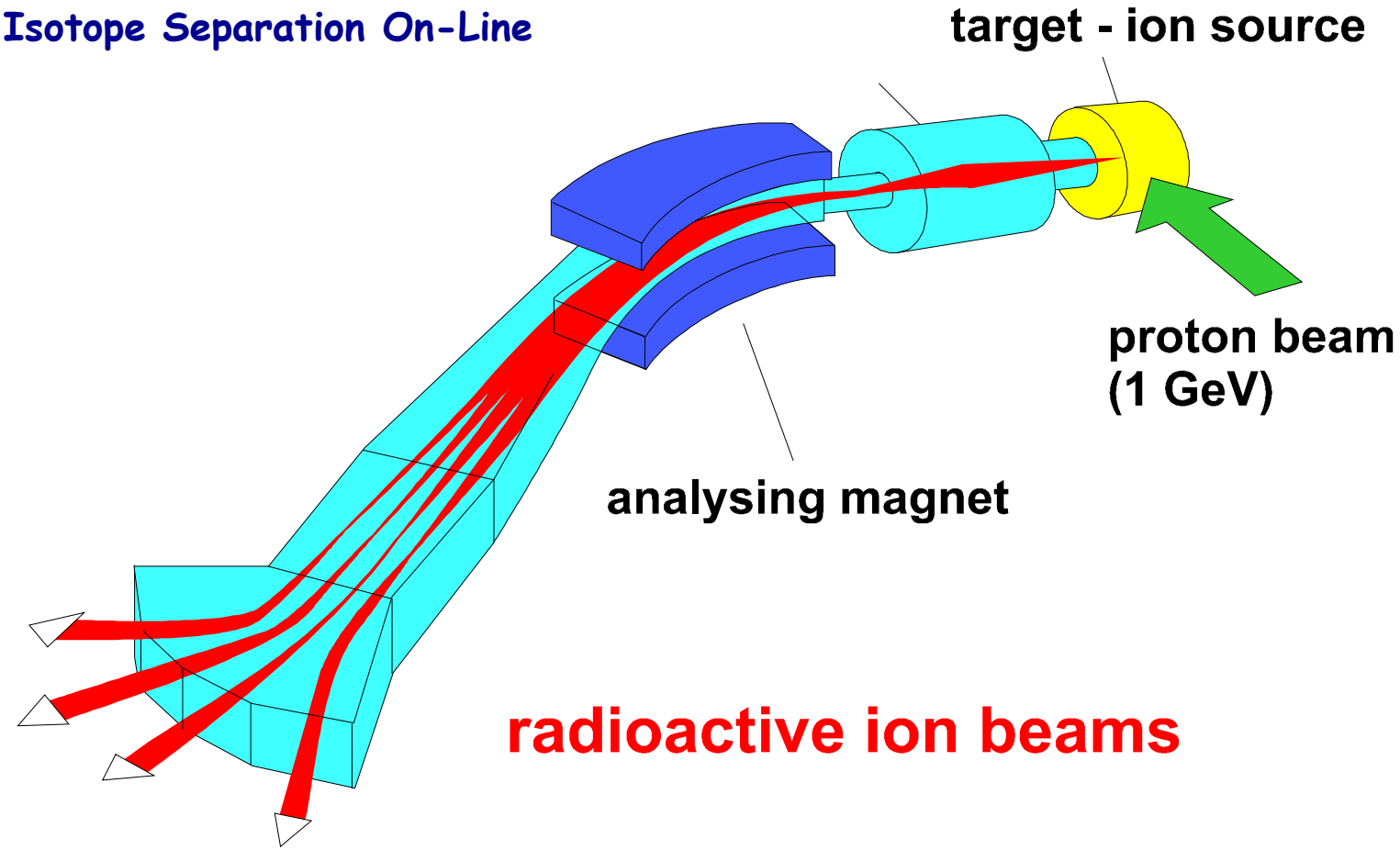
Laser Ionization source





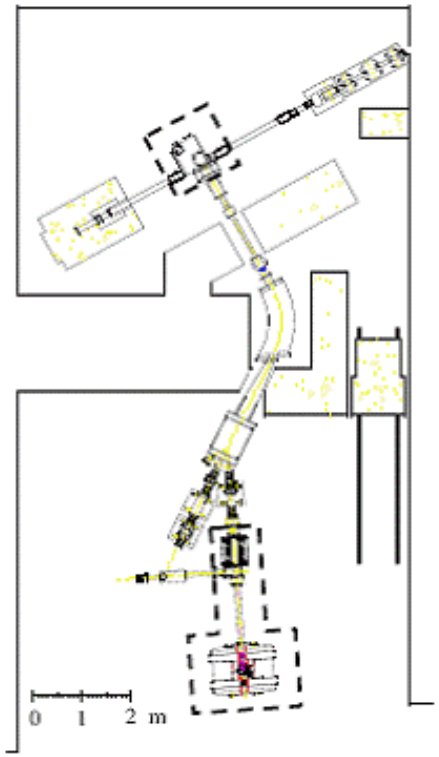
ISOL

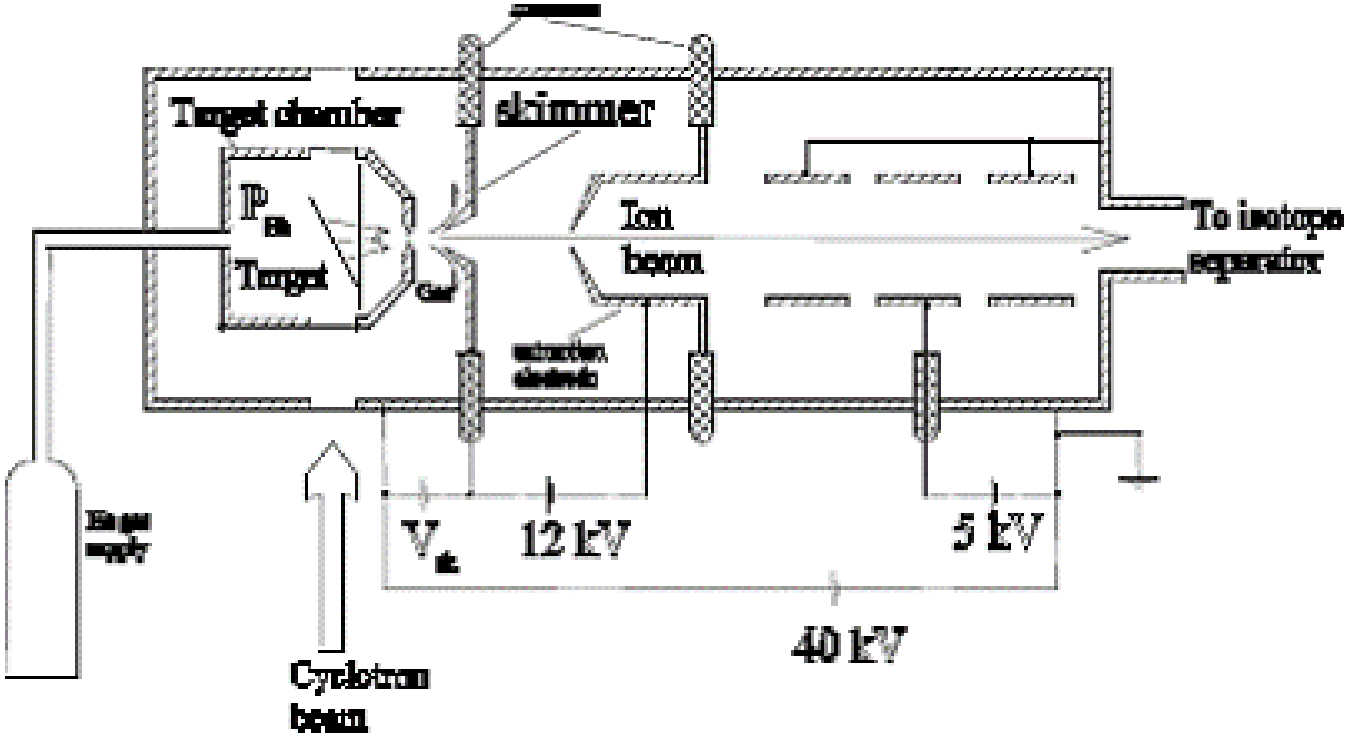
Isotope Separation On-Line



radioactive ion beams

IGISOL

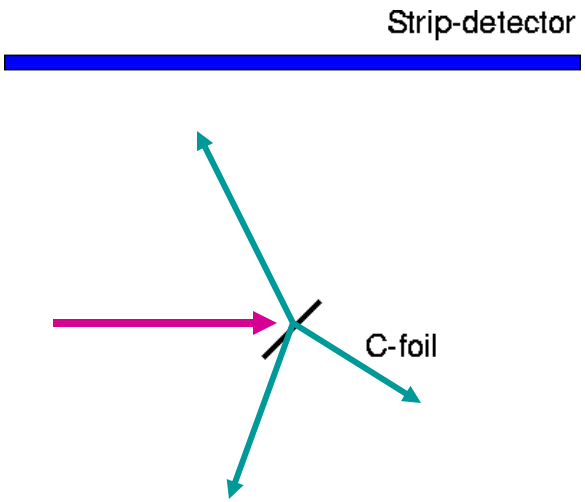


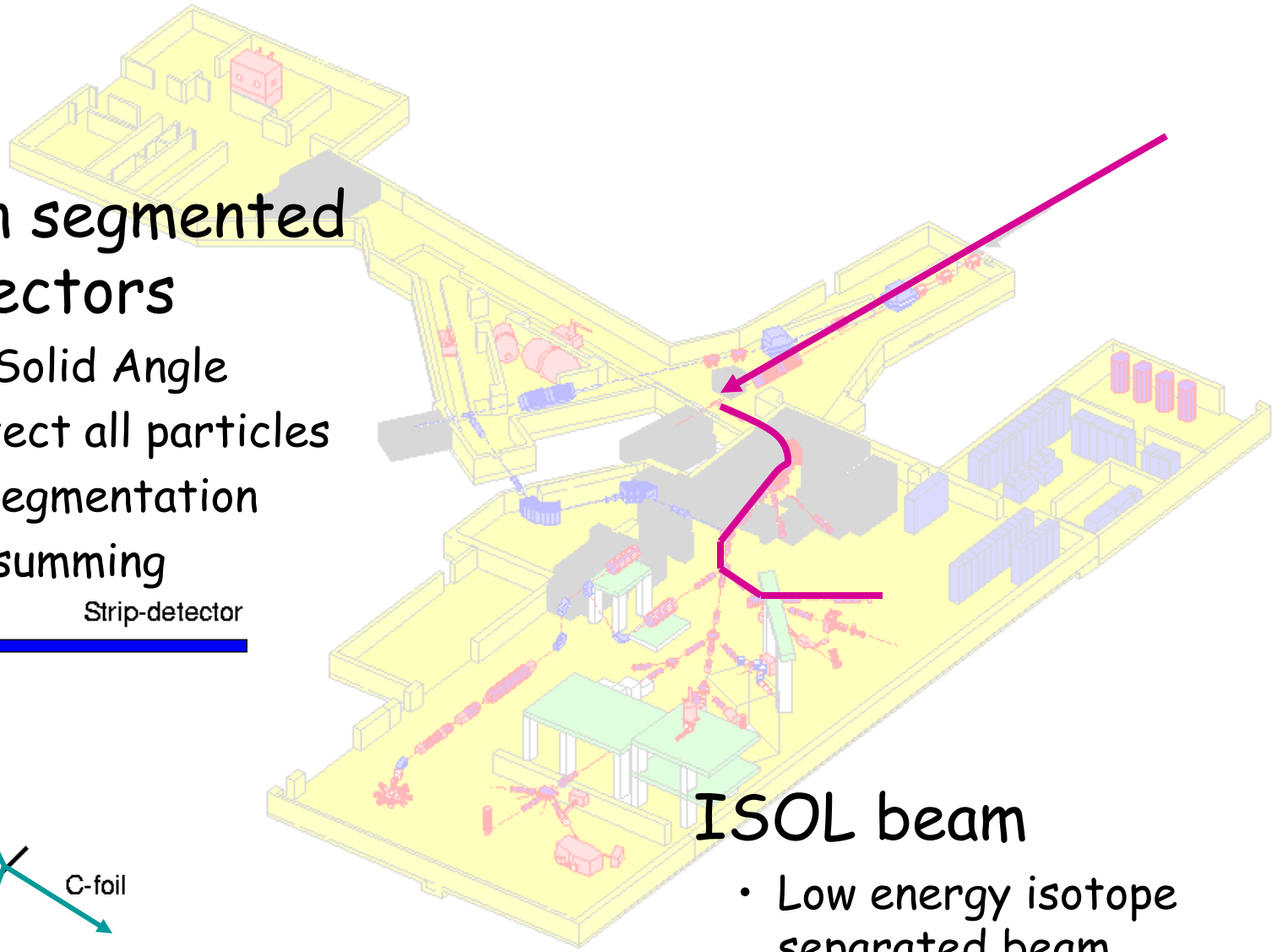


Specific features

- fast (sub ms)
- chemically non-selective
  → access to all elements including refractory metals

- Modern segmented Si-Detectors
  - Large Solid Angle
    - detect all particles
  - High Segmentation
    - no summing

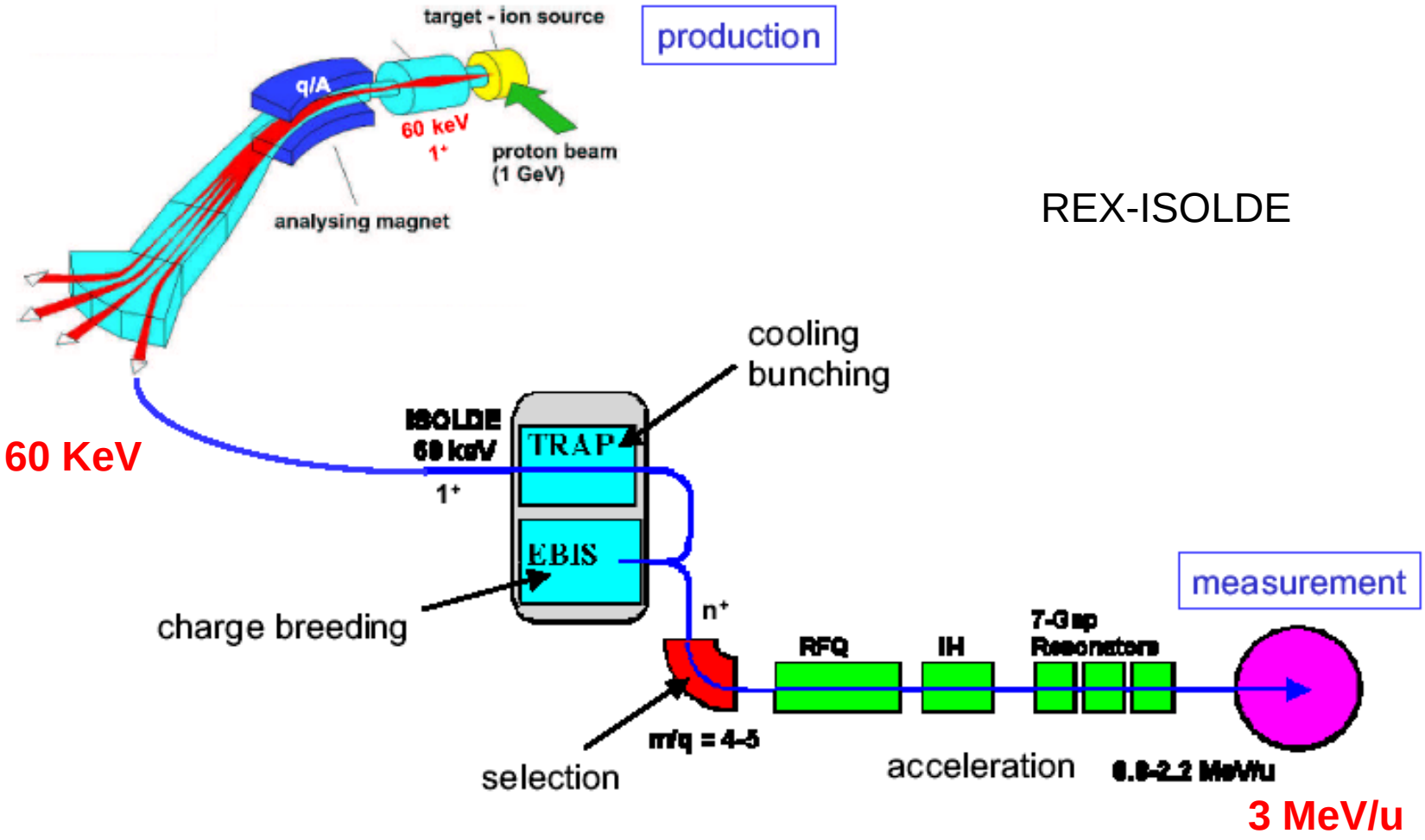




ISOL beam

- Low energy isotope separated beam
- Can be stopped in C-foil
- Well-defined source

REX: Radioactiv Beam Experiment @ ISOLDE
first beam in 2001



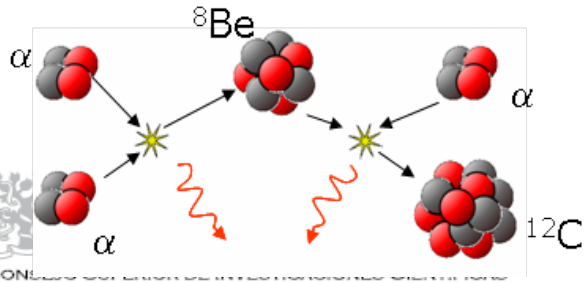
Light exotic Nuclei

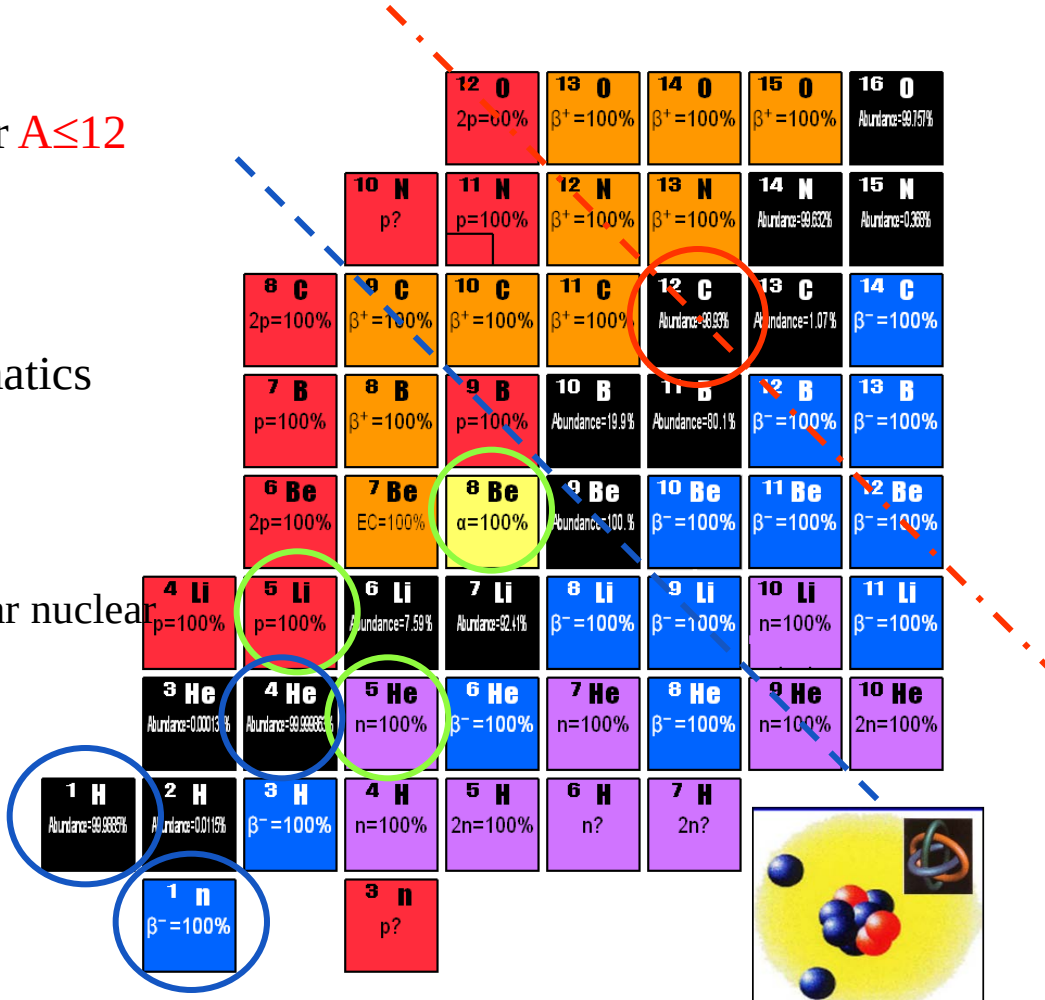
- "Exact" A-body calculations possible for A≤12
  - Shell-model states
  - Molecular-cluster states
- We cover from drip-line to drip-line
- Break-up mechanism not fixed by kinematics
  - Sequential?
  - Direct?
- Crucial for bridging the
  - A=5 and A=8 gaps in Big Bang and Stellar nuclear synthesis.

^{12}C & The triple alpha process

$^{4}He + {}^{4}He \leftrightarrow {}^{8}Be$

$^{8}Be + {}^{4}He \leftrightarrow {}^{12}C + \gamma + 7.367\ MeV$





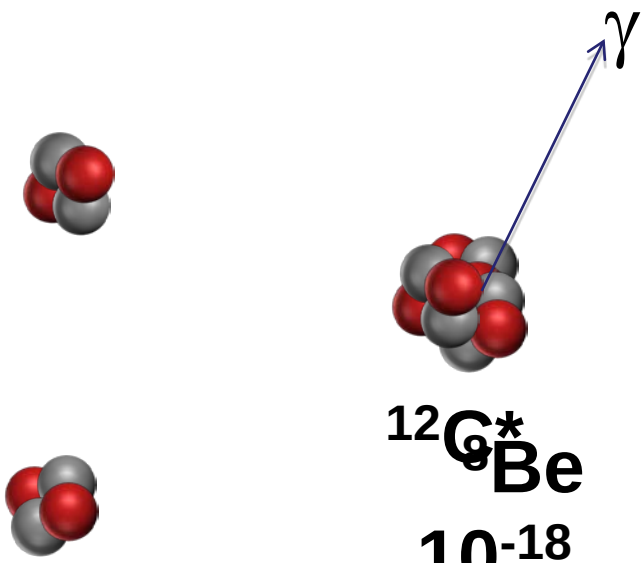
clustering

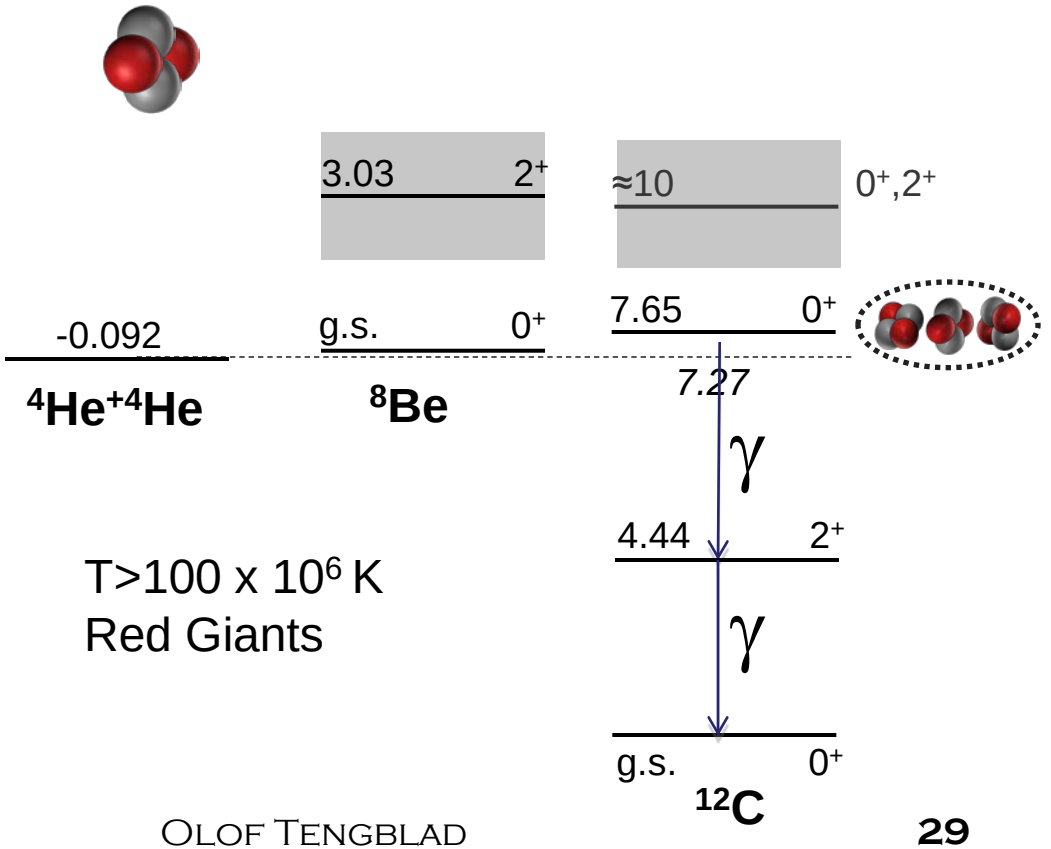
11Li → Borromean Halo

Triple-α Process

N6. A State in C^{12} Predicted from Astrophysical Evidence.* F. Hoyle, *Cambridge University* and D. N. F. Dunbar, W. A. Wenzel, and W. Whaling, *Kellogg Radiation Laboratory, California Institute of Technology.*—It is

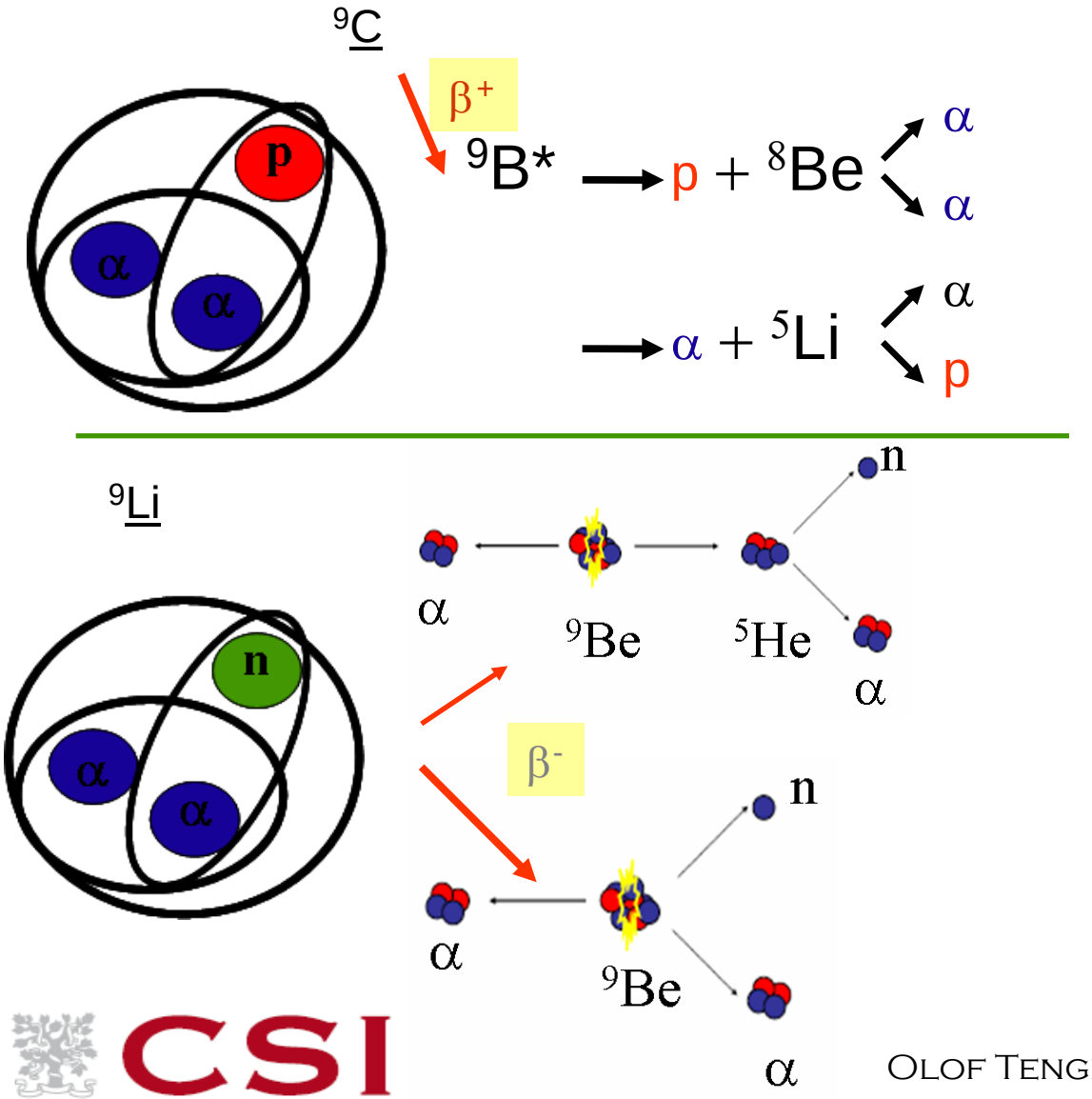
Phys. Rev. 92:1095 (1953)

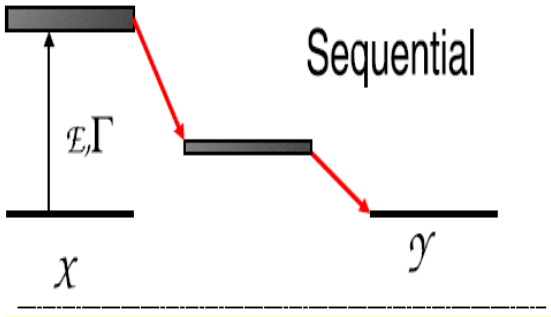




T>100 x 10^6 K
Red Giants

break-up mechanism: α-clustering?





Low energy reaction study @ Madrid Tandem accelerator – how to produce the $^{12}C^*$ states

$A+a \rightarrow C^* \rightarrow B^*+b$

^3He @ 2.5-8.5 MeV

17 mg/cm^2

+ ^{10}B → $^{13}N^*$ → p + $^{12}C^*$ + $^9B^*$ + α + α + α + α

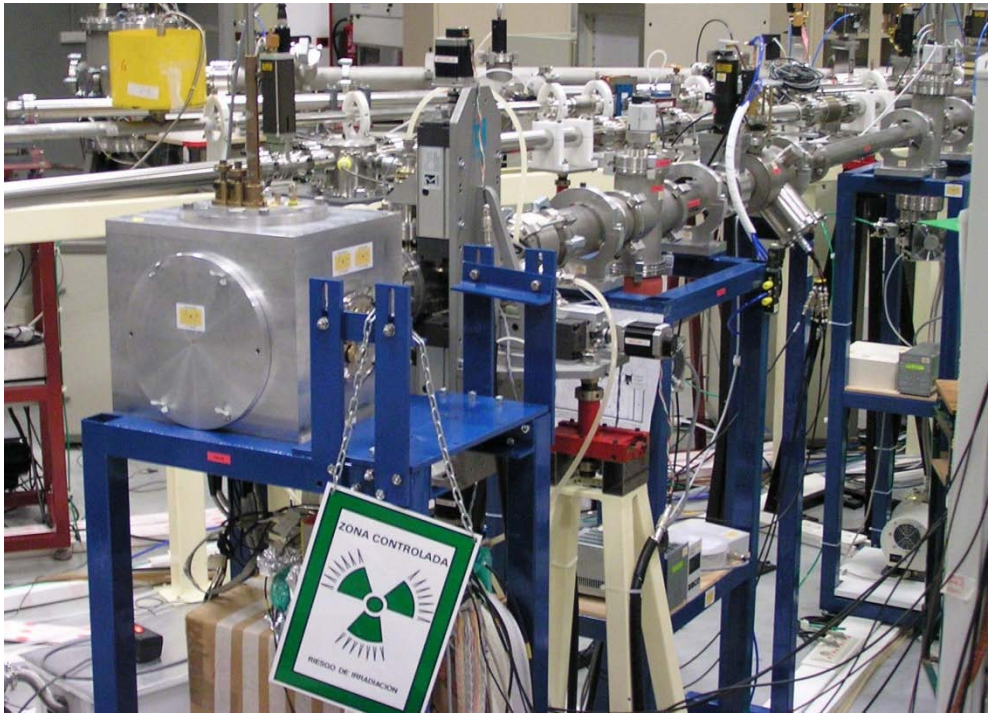
We cannot reproduce the triple alpha process directly, but we can study the states involved using two complementary methods;

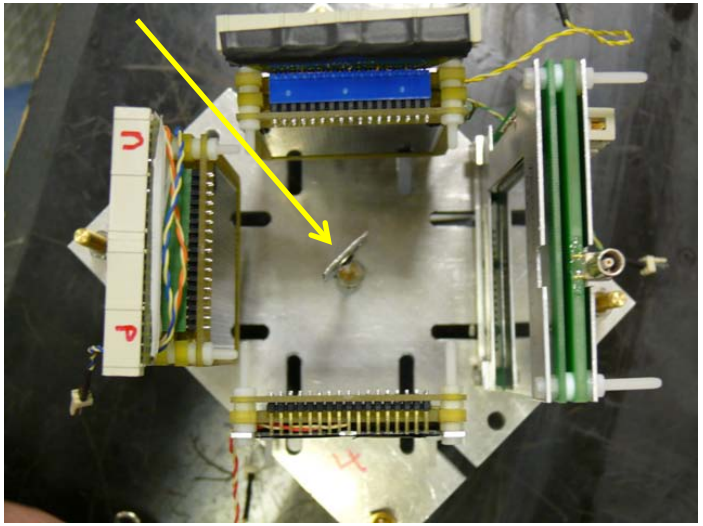
1) In beta decay from ^{12}B or ^{12}N JYFL, ISOLDE, KVI

1) Via the ^3He + ^{10}B reaction, which allows us to gain complementary information on the ^{12}C resonances

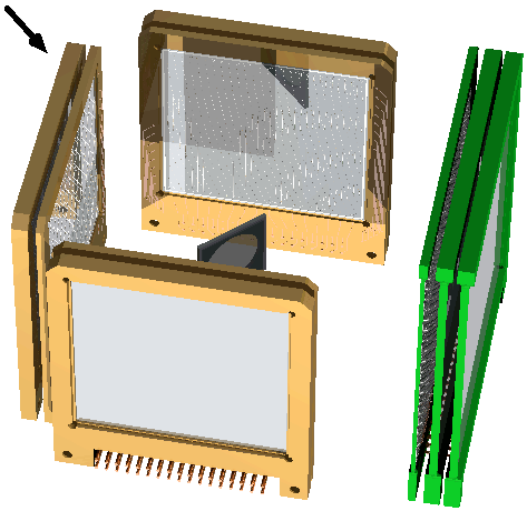
$^{10}B(^{3}He,p)\alpha\alpha\alpha$ $^{11}B(^{3}He,d)\alpha\alpha\alpha$

^{3}He @ 4.9 and 8.5 MeV from 5 MV Tandetron





DSSD + PAD



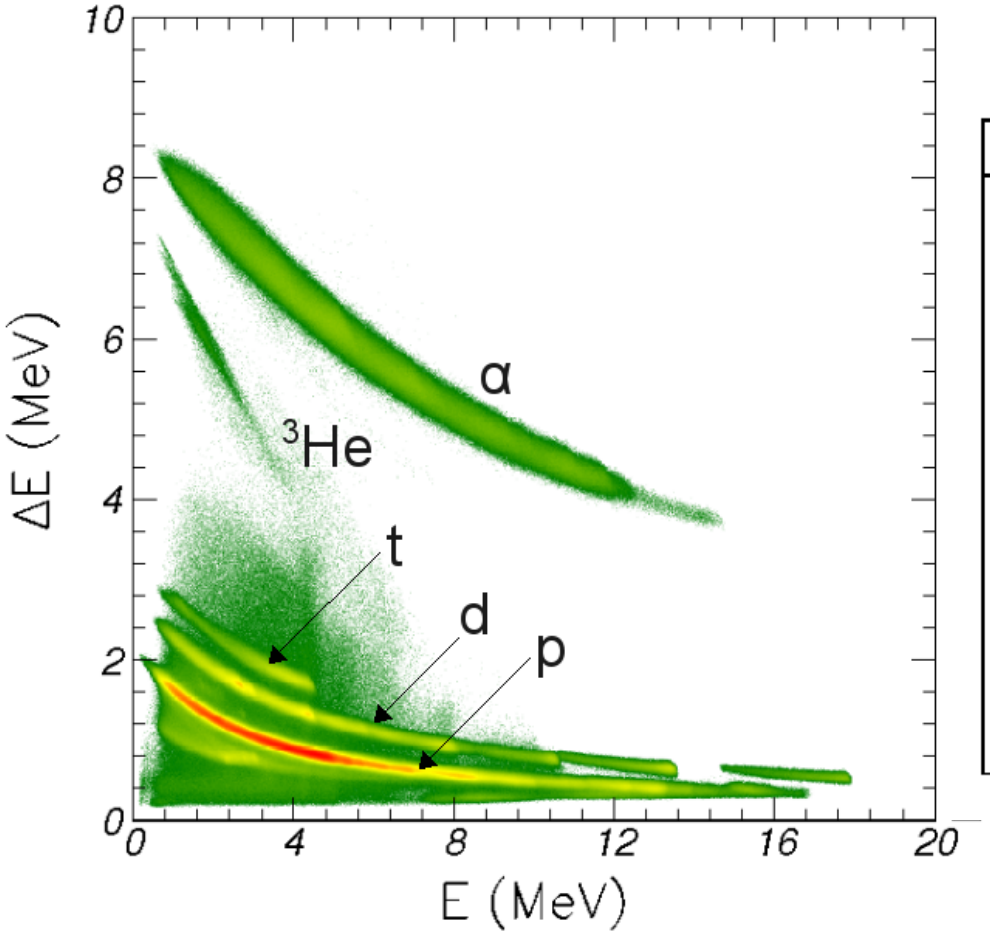
Targets:

18.9 μg/cm^2 **^{10}B** 4 μg/cm^2 C-backing

22.0 μg/cm^2 **^{11}B** 4 μg/cm^2 C-backing

Particle Identification

$^{3}He + {}^{10}B \longrightarrow d + {}^{12}C^{*}$



α + $^{9}B^{*}$

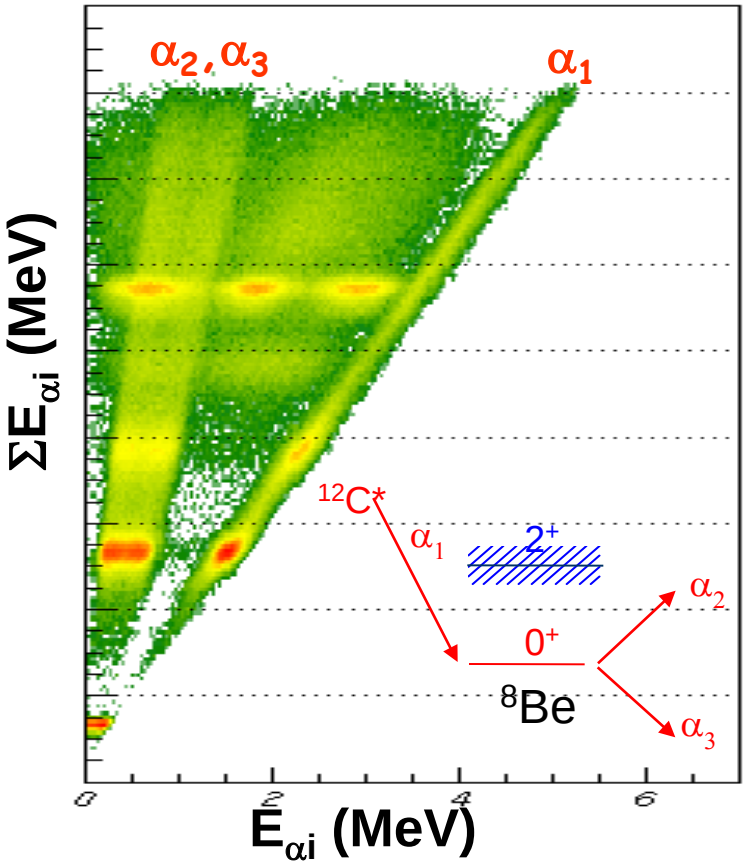
d + ^{11}C

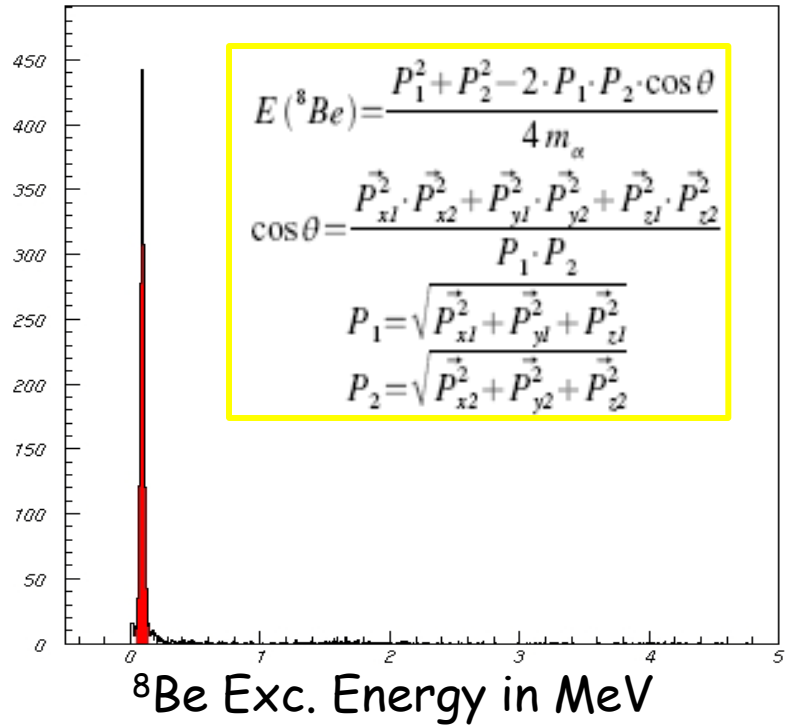
p + $^{12}C^{*}$

Reaction products	Q-Value (MeV)
$^{13}N + \gamma$	21.63668
$^{12}C + p$	19.69315
$p + 3\alpha$	12.41836
$^{8}Be + p + \alpha$	12.32652
$^{9}B + \alpha$	12.14145
$^{5}Li + 2\alpha$	10.45334
$^{11}B + 2p$	3.73607
$^{11}C + d$	3.19574
$^{12}N + n$	1.57257
$^{11}C + p + n$	0.97115
$^{10}B + ^{3}He$	0.00000

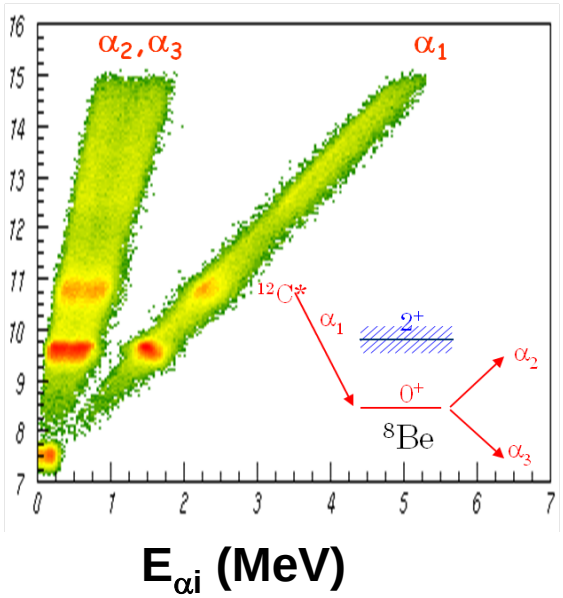
Decay Mechanism

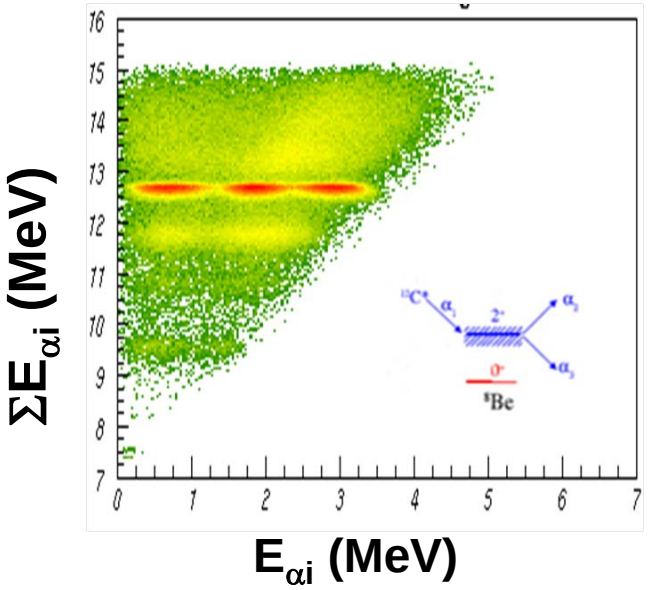
$^{3}He + {}^{10}B \rightarrow \mathbf{p} + {}^{12}C^{*} \rightarrow \alpha+\alpha+\alpha$





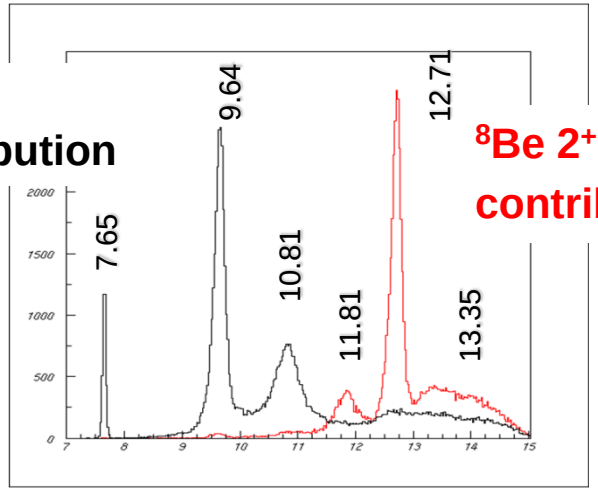
Decay Mechanism: $^{3}He + {}^{10}B \rightarrow p + {}^{12}C^{*} \rightarrow \alpha+\alpha+\alpha$





^{8}Be 0^{+} contribution

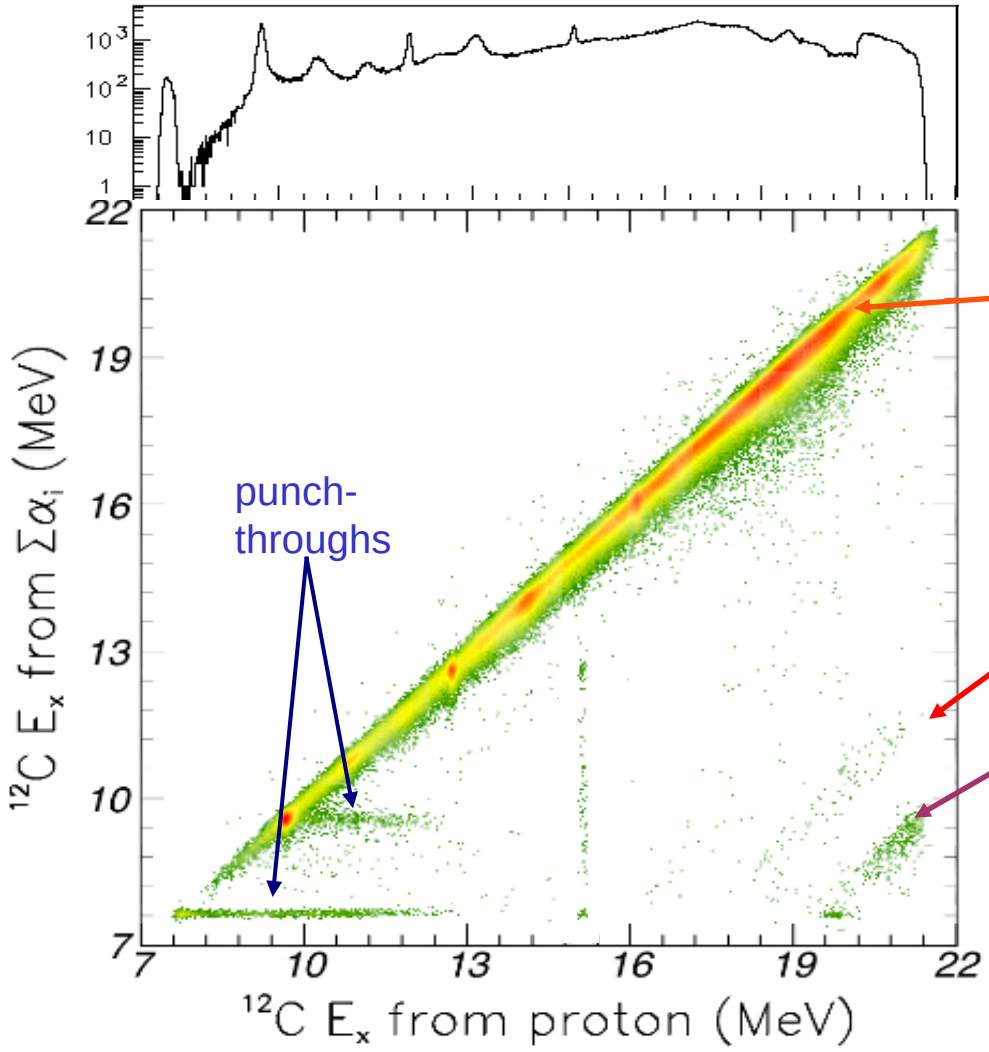
^{8}Be 2^{+} contribution



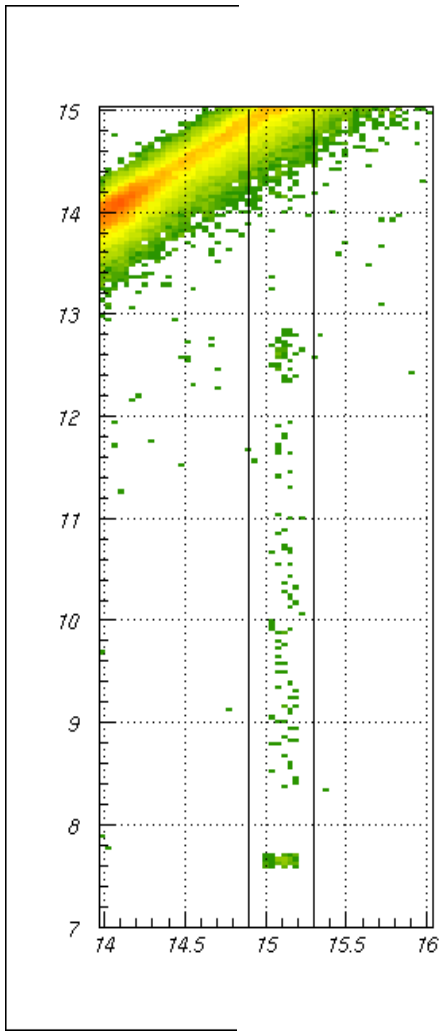
Branching Ratios

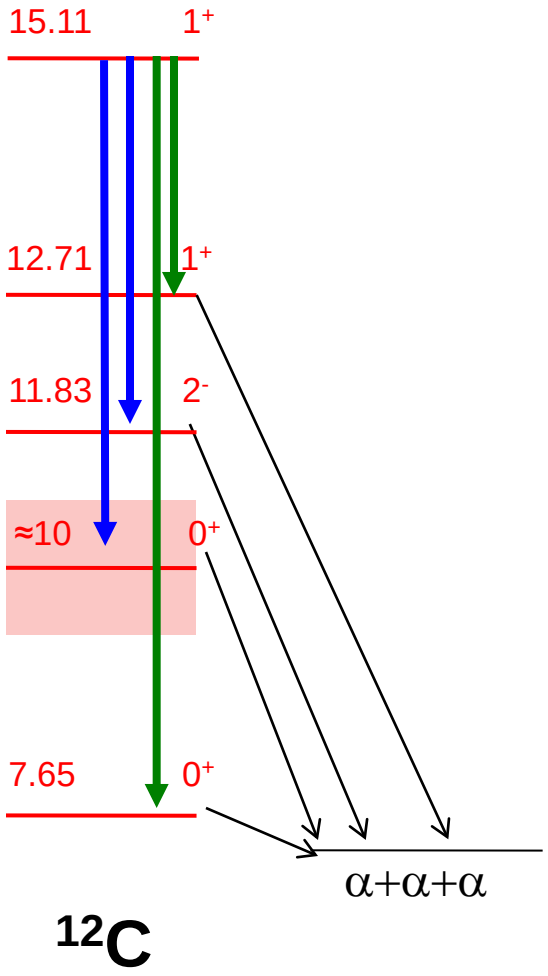
^{12}C Energy	Be (0^+)	Theory	J^π
9.6 MeV	96%	96%	3^-
10.8 MeV	75%	70%	1^-
11.8 MeV	0%	-	2^-
12.7 MeV	0%	-	1^+
13.4 MeV	0%	-	(2^-)

γ-decay of the T=1 level @ 15.11 MeV



γ-decay of the T=1 @ 15.11 MeV





M. Alcorta et al, NIM A605, 318-325 (2009)

O.S. Kirsebom et al, Phys.Lett B680, 44-49 (2009)

Summary

I have discussed different methods to produce and study radioactive nuclei

The different methods are complementary and lets us to study the nuclear system at different energies.

Our goal is to obtain more and more precise data in order to test and improve upon the theoretical models with the fin to be able to make better predictions of nuclei and systems we cannot yet produce.

^{12}C the bases of life and our mass reference can also be an exotic nuclei!

"Branching ratios in the beta decays of 12N and 12B"
Physical Review C (Vol.80, No.4):

Thank you for your attention